ARMATURE WINDING

A PRACTICAL ANALYSIS OF ARMATURE WINDINGS FOR DIRECT-CURRENT AND ALTERNATING CURRENT MACHINES, INCLUDING RULES AND DIAGRAMS FOR RECONNECTING INDUCTION MOTOR ARMATURES

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INTRODUCTION

WITH the discovery of electro-magnetism as a source of energy, electrical science progressed from an interesting phenomenon to the beginning of modern industrial development. Picture the world today without the dynamo, the electric light, electric cars, the telephone or the wireless telegraph. In a few short years this much progress has been made, and with the present knowledge of electrical science, what may not be done during the lifetime of present scholars and experimenters?

¶ As the armature, with its windings of insulated wire, is the heart of the whole system of electrical energy, should not this phase receive special study? We think so, and it is with the purpose of showing the practical and theoretical considerations due the subject of armature winding that this volume has been prepared.

¶ For many years only an inkling of the principles of electrical energy was known. From time to time discoveries, the result of experiment rather than calculation, led inventors nearer and nearer to one hundred per cent in electrical efficiency. Long observations of electrical effects led to more or less empirical formulas, which have been corrected from time to time as additional observations corrected original impressions. Advances in mechanical and chemical processes have aided in making electricity the willing servant of mankind until today the weight of the water in the mountain stream traveling from the far-off hills to the distant sea becomes, through the armature of the dynamo, the energy which lights our cities, turns the wheels of industry and carries our messages around the world. The development of the armature has thus had much to do with bringing about this happy condition in our economic existence.

¶ In preparing this volume the author has drawn heavily upon his wide experience in the theoretical and practical design of

electrical apparatus. Practically all of the line drawings have been drawn especially for this work, while the photographic reproductions represent the best practice of modern shops. Among the illustrations will be found many blue-print reproductions, indicating in the most practical method the principles of correct armature design and construction.

¶ Such advances have been made since present workmen were in school that it has become necessary for many to supplement school knowledge with information brought down to date. This volume is therefore particularly adapted for purposes of home-study and self-instruction. The treatment of each subject will appeal not only to the technically trained expert but also to the beginner and the shop-taught practical man who wishes to keep abreast of modern progress. Without sacrificing any of the essential requirements of thorough practical instruction the author has avoided many of the heavy technical terms and formulas of higher mathematics, producing a book in clear and simple language, on this important branch of electrical work.

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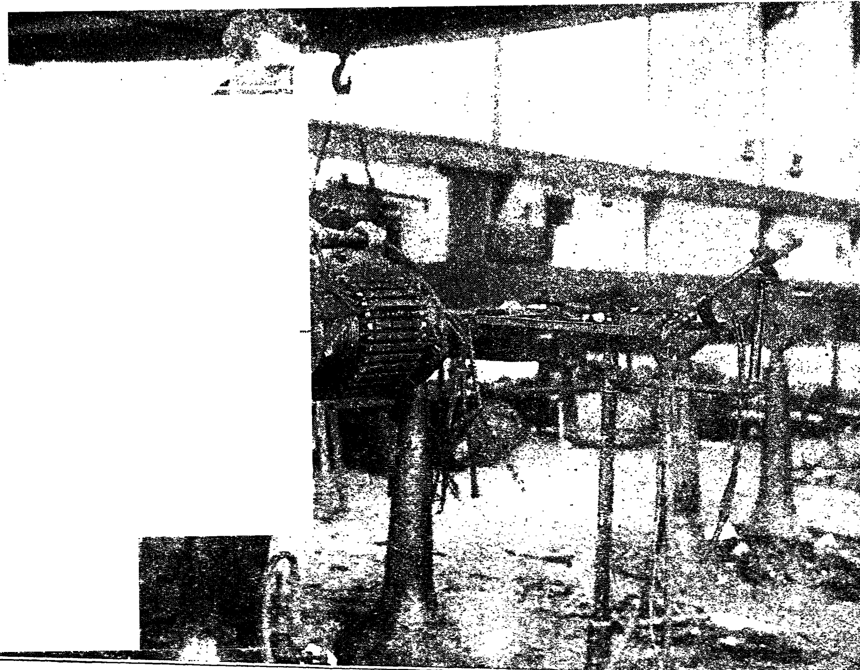


Winding the Armature of a Railway Motor
Courtesy of Westinghouse Electric and Manufacturing Company

ARMATURE WINDING

PART I

INTRODUCTION

Essential Parts of a Dynamo. The dynamo is a machine for converting mechanical energy into electrical energy or electrical energy into mechanical energy. When it is used in transforming mechanical into electrical energy, it is called a generator; and when it transforms electrical into mechanical energy, it is called a motor. The great majority of dynamos have the following essential parts: the magnetic field; the armature winding; the commutating and collecting devices (not required in all machines —the squirrel-cage induction motor, for example); and the necessary mechanical structure, such as bed plate, iron composing the magnetic circuit and its supporting structure, armature core, bearing supports, etc.

Magnetic Field. The function of the magnetic field is to provide a magnetic flux, which is cut by the inductors forming the armature winding.

Armature Winding. The armature winding is composed of a large number of wires, called inductors, in which an electromotive force (e.m.f.) or electrical pressure is induced when there is a relative movement of these inductors with reference to the magnetic field of the machine.

Commutator or Collecting Rings. The function of the commutating and collecting devices is to bring about the necessary reversal of connections between the various elements composing the armature winding and the external circuit, and at the same time to provide the necessary continuous electrical connection between the circuits on the moving part of the machine and the outside circuits.

Mechanical Parts. The function of the various mechanical parts is obvious, and the iron composing the magnetic circuit

the armature core serves as a mechanical support for the armature windings.

In commercial continuous-current machines, the field magnet is nothing more than a simple electromagnet which remains stationary, but the armature is a great deal more complex and always rotates. In alternating-current machines either the armature or field may be stationary. Continuous-current machines always require a commutator, which is mounted on the same shaft as the armature, while the alternating-current machines are provided with slip rings when an electrical connection must be established between the rotating part of the machine and an outside circuit.

The development of the various forms of armature windings for both continuous- and alternating-current machines will be discussed in the following sections.

Producing an E.M.F. by Cutting Magnetic Lines of Force. When a conductor and a magnetic field are caused to move relative to each other, so that the imaginary lines of force that are supposed to compose the magnetic field are cut by the conductor, there will be an e.m.f. induced in the conductor.

E.M.F. Depends on Rate Lines Are Cut. The value of this induced e.m.f. at any instant will depend upon the rapidity with which the lines of force are being cut by the conductor at that particular instant. If the lines of force are being cut at a perfectly uniform rate, that is, if the same number are cut in each succeeding fractional part of a second, say one hundredth part of a second, and there is a total of 100,000,000 lines cut in one second, then there will be an e.m.f. of one volt induced in the conductor. Thus if a horizontal conductor 50 centimeters long be moved downward across a horizontal magnetic field whose intensity is 20,000 gausses, as indicated in Fig. 1, at a uniform velocity of 10 centimeters each second, all the magnetic lines in the area 10×50 centimeters will be cut in one second. Since there are 20,000 magnetic lines passing through each unit of area, then the total number of magnetic lines cut by the conductor in one second will be equal to $10 \times 50 \times 20000$, or 10,000,000. Dividing 10,000,000 by 100,000,000 gives 0.1 volt, the value of the e.m.f. induced in the conductor

If the conductor be moved at a greater velocity, say twice as fast, then the e.m.f. induced will be equal to twice the stated value, and if its velocity be decreased there will be a corresponding decrease in the induced e.m.f. If the strength of the magnetic field be increased or decreased in value, there will be a corresponding increase or decrease in the value of the induced e.m.f. Likewise, if the length of the conductor in the magnetic field, or that part of the conductor which is actually cutting lines of force, be increased or decreased, there will be a corresponding increase or decrease in the value of the induced e.m.f.

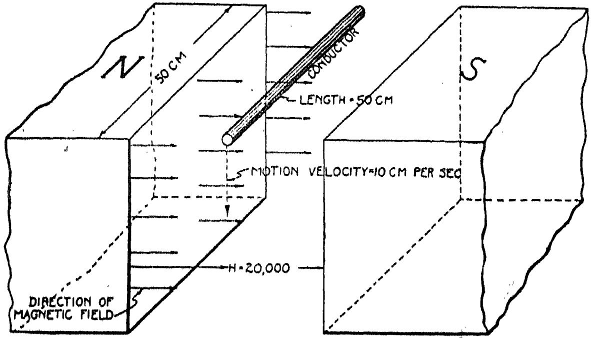


Fig. 1. Horizontal Conductor Moving Downward across a Uniform Magnetic Field—Motion Perpendicular to Field

If this conductor be made to form part of a closed electrical circuit, there will be a current of electricity produced in the circuit due to the e.m.f. induced in the conductor.

Right-Hand Rule. There is a definite relation between the direction of the magnetic field, the direction of motion of the conductor, and the direction of the induced e.m.f., which is as follows: If the first and second fingers and the thumb of the right hand be placed at right angles to each other and in such a position that the first finger points in the direction of the magnetic field and the thumb points in the direction of motion, then the second finger will point along the conductor in the direction of the induced e.m.f. The direction of the induced e.m.f.

the magnetic field be reversed. If the direction of the magnetic field and the motion both be reversed, then the direction of the induced e.m.f. will remain the same.

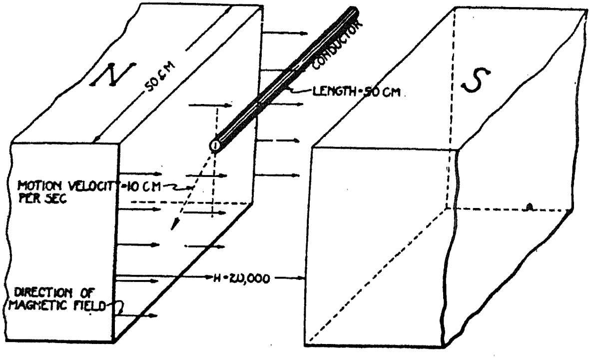


Fig. 2. Horizontal Conductor Moving Downward across Uniform Magnetic Field—Motion Not Perpendicular to Field

The motion of the conductor in Fig. 1 is perpendicular to the direction of the magnetic field, and, as a result, more magnetic lines are cut by the conductor when it moves a certain distance along its path than would be cut if the motion of the conductor were along a path making an angle of less than 90 degrees with the direction of the magnetic field, Fig. 2. In Fig. 2 it is the component of the velocity of the conductor per-

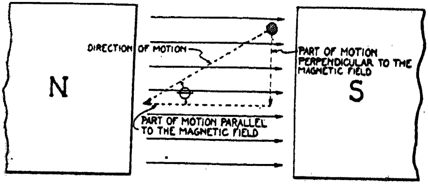


Fig. 3. Motion of Conductor Resolved into Two Components—One Perpendicular to Field and One Parallel to Field

pendicular to the direction of the magnetic field that determines the rate of cutting of the magnetic lines. This component of the velocity of the conductor is equal to the actual velocity

multiplied by the sine of the angle between the direction of t magnetic field and the direction of motion of the conduct Thus in Fig. 3, if the angle θ is equal to 30 degrees, and other conditions are the same as in the above problem, th when the conductor moves a distance of 10 centimeters it h moved a distance perpendicular to the magnetic field equal $10 \times \text{sine } 30°$, or 10×0.5, which equals 5 centimeters. The ra at which the conductor is actually cutting the magnetic lines then, just one-half of what it was originally, and the e.m.f. induc in the conductor will be one-half as great, or 0.05 volt.

SIMPLE GENERATOR

Analysis of Operation. *Straight Conductor.* When the co ductor, Fig. 1, has moved downward a sufficient distance to l out of the magnetic field, there will be no e.m.f. induced in it, as it continues to move on down, for there will be no magnetic lines of force cut by the conductor. Now, in order that the conductor may continue cutting the magnetic lines of force, it will be necessary for the motion of the conductor to be reversed when it reaches the edge of the magnetic field in its downward travel; that is, the motion of the conductor must be alternately up and down across the magnetic field. If the strength of the magnetic field is uniform in the region in which the conductor moves and the velocity of the conductor is constant and the direction of its motion is reversed instantly, then the variation in the e.m.f. induced in the conductor may be represented graphically as shown in Fig. 4 Assume that the conductor starts from its uppermost position in the magnetic field, as shown at A, Fig. 5, and moves at a constant velocity downward across the magnetic field to its lowermost position, as shown at B, Fig. 6 During this time the conductor is cutting the magnetic lir a constant r te for all r it

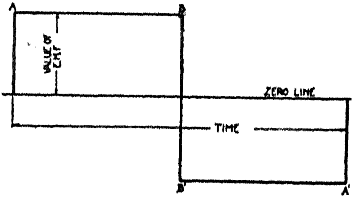


Fig. 4 Curve Representing Variation in Value c Electromotive Force Induced in a Conductor Tha Is Moved Back and Forth across a Uniform Magneti Field at a Constant Velocity

induced in it is constant, as represented by the upper part of the line AB, Fig. 4. The height of the horizontal line AB above the zero line is a measure of the e.m.f. induced in the conductor. Now when the conductor reaches the lowermost position, it immediately starts to move upward across the magnetic field at the same rate it was originally moving downward across the field, and, as a result, the value of the induced e.m.f. will be the same but its direction will be exactly opposite what it was originally This fact is shown diagrammatically in Fig. 4 by the line $B'A'$, which is parallel to the zero line and exactly the same distance below the zero line as the line AB is above the zero line. The

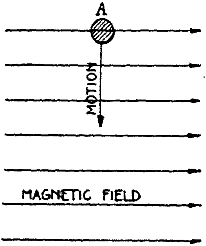


Fig. 5. Conductor Entering Magnetic Field and Moving Downward across Same

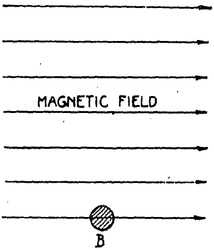


Fig 6 Conductor at Lower Edge of Magnetic Field

lengths of the lines AB and $B'A'$ are drawn to represent time to any convenient scale; thus each inch may correspond to one second, etc.

Action of Loop. The arrangement just described may be greatly improved upon by revolving a loop of wire in a magnetic field, as shown in Fig. 7 Four positions of the loop are shown in cross-section in Fig. 8, and the e.m.f induced in the loop for these different positions may be determined as follows: In position *1* the plane of the loop is perpendicular to the direction of the magnetic field, and if the loop be rotated a small angle about its axis, there will be no e.m.f induced in it because there are no magnetic lines cut by any part of the loop. The two sides of the loop will be moving parallel to the magnetic field, and hence cutting no lines of force; while the planes in which the two ends [illegible] rallel to the direction of the magnetic field, and

hence the ends will never cut across any of the lines of force forming the magnetic field, regardless of the angular position of the coil, so long as the axis of the loop is perpendicular to the direction of the magnetic field.

In position *2* the plane of the loop is parallel to the magnetic field and the two sides of the loop are moving perpendicular to the magnetic field for an instant while the loop is in this position. Since the sides of the loop are moving perpendicular to the direction of the magnetic field, when the loop is in position *3* they will be cutting the magnetic lines at the greatest possible rate.

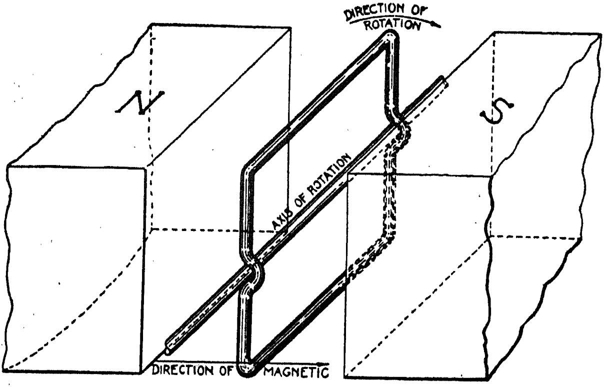


Fig. 7. Closed Loop of Wire Revolving in a Uniform Magnetic Field

In position *3* the plane of the loop is perpendicular to the direction of the magnetic field and the e.m.f. induced in the two sides is zero, for the same reasons as those given for position *1* In position *4* the plane of the loop is parallel to the direction of the magnetic field and the two sides are moving perpendicular to the direction of the magnetic field just as explained for position *2*. In position *2*, however, the side E is moving downward across the magnetic field and the side F is moving upward across the magnetic field, while in position *4* just the reverse is true; that is, side E is moving upward across the magnetic field, and side F is moving downward across the magnetic field. Th

in the two sides will be in opposite directions for all positions of the loop as you look along the two sides, but it will be observed that they are acting together around the loop rather than opposing each other, for all positions of the loop.

From position *1* to position *3*, the side E is moving downward across the magnetic field and the side F is moving upward across the field, while from position *3* back to position *1* the side E is moving upward across the magnetic field and the side F is moving downward. As a result of this relation between the direction of motion of the sides of the loop and the direction of the magnetic

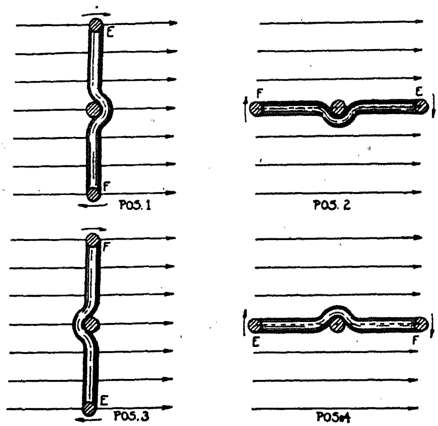


Fig. 8. Four Different Positions of a Loop as It Revolves in a Magnetic Field

field, there will be an electrical pressure induced in the loop which will act around the loop in a certain direction while the loop is rotating from position *1* to position *3* and around the loop in the opposite direction while rotating from position *3* to *4* and on back to position *1*, or the starting point.

Variations of E.M.F. in One Revolution. The value of the e.m.f. in the loop does not remain constant, but changes in value as the position of the loop in the magnetic field changes, the reason being that the velocity of the sides across the magnetic lines of force for a certain constant angular rotation of the loop

is continuously varying in value. The maximum velocity that the two sides of the loop can have across the magnetic field occurs when the loop is parallel to the magnetic field or in position *2* or *4*, Fig. 8. The component of the velocity of the sides of the loop, which is actually perpendicular to the direction of the magnetic field when the loop is in any position whatever, may be expressed in terms of the maximum velocity which the sides may have and the angular position of the loop with reference to the plane perpendicular to the magnetic field and corresponding to position *1* of the loop. Thus in Fig. 9 the side of the loop is shown between positions *1* and *2*, and the plane of the loop is making the angle θ with position 1. The component of the velocity of the side of the loop, which is perpendicular to the direction of the magnetic field, is equal to the velocity of the side of the loop multiplied by the sine of the angle θ. Thus if the angle θ is equal to 60 degrees, then the velocity of the side of the loop, perpendicular to the direction of the magnetic field will be equal to V sine 60°, or $V \times 0.866$. Since the e.m.f. induced in the side of the loop depends upon the component of the velocity of the side of the loop perpendicular to the magnetic field, all other things being constant, and since this component of the velocity of the side of the loop varies as the sine of the angle θ in Fig. 9, then it follows that the e.m.f. induced in the sides of the loop for any position will be equal to the e.m.f. in the side of the loop for positions *2* and *4* multiplied by the sine of the angle θ. The e.m.f. induced in the sides of the loop is a maximum for positions *2* and *4* and may be represented by $E_{max.}$ and for any other position it will be equal to $E_{max.}$ sine θ. The variation in the e.m.f. induced in the

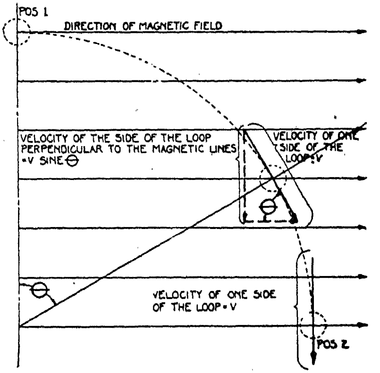


Fig. 9. Method of Determining Velocity of Side of a Loop Perpendicular to Direction of Magnetic Field at Any Instant as Loop Is Rotated at a Uniform Velocity

loop for all positions of the loop is shown diagrammatically in Fig. 10. The distances along the zero line correspond to the values of the angle θ. Such a curve is called a sine curve.

Effect of More Loops. The e.m.f. may be increased by adding more turns to the loop and connecting these turns in series so that the e.m.f. induced in the different turns acts in the same direction around the loop.

The complete set of positive and negative values represented in Fig. 10 constitutes what is called a cycle. A complete set of positive or negative values constitutes what is called an alternation. There are always twice as many alternations as there are cycles. The number of complete cycles that occur in one second is called the frequency. In Fig. 10 one revolution of the loop constitutes a cycle, or two alternations; and if the loop is made to revolve at the rate of 60 revolutions per second, the frequency of the induced e.m.f. will be 60 cycles.

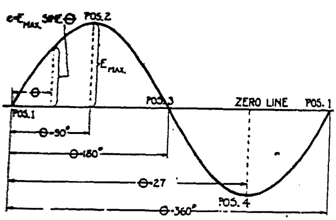


Fig. 10. Curve Representing Variation in Value of Electromotive Force Induced in a Loop That Is Rotated at a Uniform Angular Velocity in a Uniform Magnetic Field

Function of Slip Rings. In order to make use of the e.m.f. generated in the loop, Fig. 7, in producing a current in an electrical circuit, it is necessary to provide some means of connecting the loop in series with the circuit in which the current is to be produced. Such an electrical connection may be provided by opening up the loop and connecting the two ends thus formed to two continuous metal rings, mounted on the axis of the loop and insulated from each other. Upon these rings are two metal or carbon brushes, connected to the external circuit, as shown in Fig. 11. Such a device constitutes a simple alternating-current generator. A complete discussion of the armature windings for alternating-current machines will be given in the section "Armature Windings for Alternating-Current Machines."

Function and Operation of Two-Part Commutator. As the loop of wire in Fig. 11 is made to revolve, an e.m.f. will be induced in it, and this e.m.f. will reverse in direction twice every

revolution, as shown by the curve in Fig. 10. If the external circuit be closed, the alternating e.m.f. induced in the loop will produce an alternating current in the circuit. Such a current is not suitable for all purposes, as, for example charging storage batteries, and must be changed to a unidirectional or direct current. It is the function of the commutator to change the alternating current in the loop into a direct current in the external circuit and at the same time provide the necessary electrical connections between the loop and external circuit.

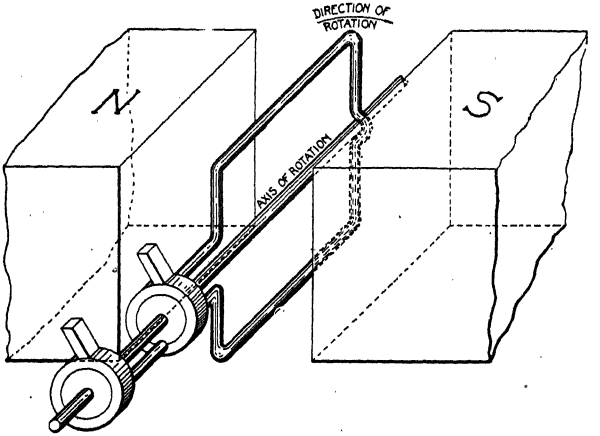


Fig. 11. Simple Alternating-Current Generator

The simplest form of commutator consists of a metal ring divided into two equal parts and mounted on a tube of insulating material, the two halves of the ring being insulated from each other. Each half of the ring should be connected to one of the ends of wire formed by opening up the loop, Fig. 12. The metal parts composing the commutator are called segments. The two segments in the commutator are shown in Fig. 12. The electrical connection to the external circuit is made by means of suitable brushes which make electrical contact with the segments of the commutator. Two brushes are required with a two-part commutator and single loop, as shown in Fig. 12, and these

brushes should be equally spaced on opposite sides of the commutator, and in such a position that the insulation between the segments of the two-part commutator is exactly in the middle of the brushes when the plane of the loop is perpendicular to the direction of the magnetic field, or the induced e.m.f. in the loop is zero. A two-part commutator of this kind will reverse the connections of the loop of wire with respect to the external electrical circuit when the e.m.f. in the loop is zero and the e.m.f. acting on the external circuit always will be in the same direction and may be represented graphically by a curve such as the one shown in Fig. 13. This kind of an e.m.f. is called a pulsat-

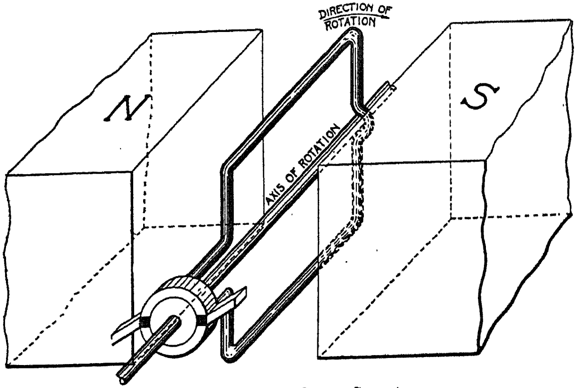


Fig. 12. Simple Direct-Current Generator

ing e.m.f. because it pulsates in value at regular intervals; it is, however, continuous in direction. In order to produce an e.m.f. nearer constant in value more commutator segments and loops of wire must be used.

Operation of Four-Part Commutator and Two Loops of Wire. The fluctuation in the value of the e.m.f. between the brushes with the arrangements shown in Fig. 12, can be reduced by using two more commutator segments and a second loop. In this case the metal ring is cut in four parts instead of two, thus forming a commutator composed of four segments instead of two. The two loops are placed at right angles to each other and the termi-

nals of each loop are connected to commutator segments that are opposite to each other instead of adjacent to each other. The connections of the loops and segments are shown in Fig. 14.

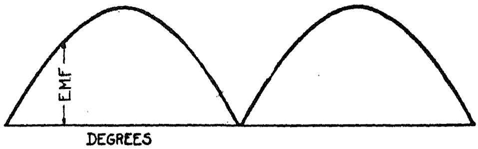


Fig. 13. Curve Representing Variation in Value of Electromotive Force between Brushes of Direct-Current Generator Shown in Fig. 12

Two brushes are required, and they should be placed exactly opposite each other and in such a position around the commutator that they pass from one segment to the next when the planes of the two loops are making angles of 45 degrees with a plane perpendicular to the direction of the magnetic field. The proper position of the brushes is shown in Fig. 14. Let us now consider the operation of this machine. Starting with loop A

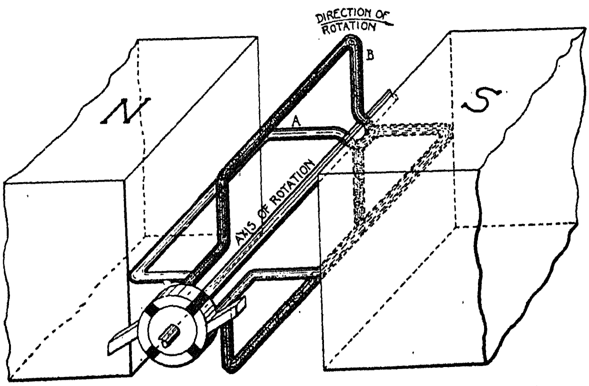


Fig. 14. Direct-Current Generator Composed of Two Loops of Wire and a Commutator of Four Segments

parallel to the magnetic field, loop B, which is at right angles to loop A, will be perpendicular to the direction of the magnetic field. When the loops are in this position the brushes should be

in the center of the segments connected to loop A. Now as the combination of loops and commutator (called the armature) rotates, the e.m.f. induced in loop A decreases in value and the e.m.f. induced in loop B increases in value (it is to be remembered at the start the e.m.f. in A is at its maximum value and the e.m.f. in B is zero). When the armature has turned through an angle of 45 degrees, the commutator segments connected to loop A move from under the brushes and the commutator segments connected to loop B move under the brushes. This results in loop B now being connected in series with the external circuit instead of loop A. Loop B will remain in electrical connection with the external circuit for the next 90 degrees' rotation of the armature, or one quarter turn, when the segments connected to

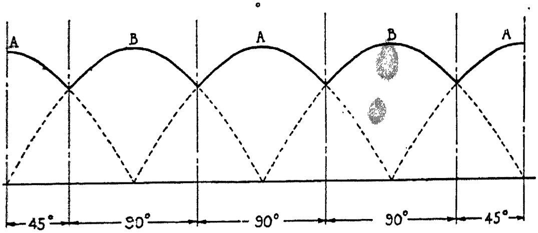


Fig. 15. Curve Representing Variation in Value of Electromotive Force between Brushes of Direct-Current Generator Shown in Fig 14

B move from under the brushes and those connected to A move under the brushes. From the above statements and a careful inspection of Fig. 14 it is apparent that the loops A and B are alternately connected to the external circuit, and each time either of them is connected it is for one quarter of a revolution of the armature. The e.m.f. between the brushes varies in value, but it will never drop to zero value as with the single loop. The connections of the loops are changed when they are making an angle of 45 degrees with a plane perpendicular to the direction of the magnetic field and the e.m.f.'s induced in the loops at this instant are equal in value and equal to 0.707 of the maximum e.m.f. induced in either loop when its plane is parallel to the direction of the magnetic field. This results in the e.m.f. between the brushes fluctuating in value between a maximum value and

0.707 of this maximum value. The fluctuation in e.m.f. for one complete revolution of the armature is shown in Fig. 15.

Operation of Six-Part Commutator and Three Loops of Wire. The fluctuation in the value of the e.m.f. between the brushes with the arrangement described in the preceding section may be decreased by using three loops of wire and a commutator composed of six segments. The terminals of each loop should be connected to two segments exactly opposite each other and the brushes should be exactly opposite each other and in such a position that they are in the center of the commutator segments connected to a loop when that loop is in a position parallel to

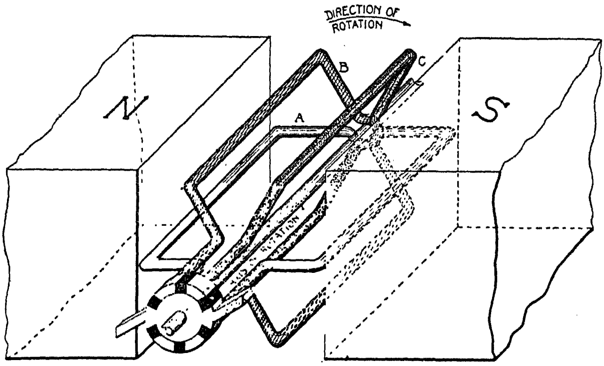


Fig. 16. Direct-Current Generator Composed of Three Loops of Wire and a Commutator of Six Segments

the direction of the magnetic field, or when the e.m.f. induced in the loop is at its maximum value. The arrangement of the loops, brushes, and commutator segments is shown in Fig. 16. Now as the armature rotates, the e.m.f. induced in loop *A* decreases in value, the e.m.f. induced in *B* decreases in value, and the e.m.f. induced in *C* increases in value. When the armature has turned through an angle of 30 degrees the segments connected to the loop *A* move from under the brushes, and the segments connected to loop *C* come into contact with the brushes and remain in contact for a rotation of the armature of 60 degrees, or one-sixth revolution. When the segments connected

to loop C leave contact with the brushes, the segments connected to loop B make contact, and remain in contact for one-sixth revolution, then loop A comes into contact again for one-sixth revolution. Then loop C for one-sixth revolution, loop B for one-sixth revolution, and back to loop A for an angular movement of 30 degrees. This brings the armature back to the starting point. The fluctuation in e.m.f. for one complete revolution of the armature is shown in Fig. 17.

Operation of Two-Part Commutator and Two Loops of Wire. Two loops of wire may be connected in parallel between two commutator segments as shown in Fig. 18. The e.m.f. between the brushes will be the same as though a single loop of wire were used, but the current the armature is capable of delivering will be doubled if the wire used in winding the loops is of the

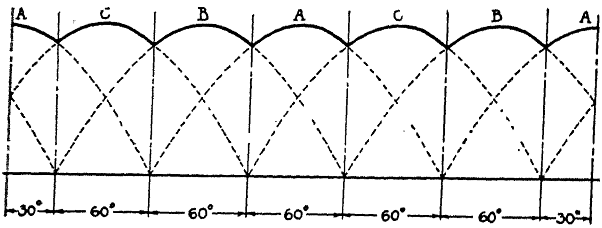


Fig. 17 Curve Representing Variation in Value of Electromotive Force between Brushes of Direct-Current Generator Shown in Fig. 16

same size as that used in winding the single loop. The variation in the e.m.f. between the brushes for such a combination is shown in Fig. 13.

Operation of Four-Part Commutator and Four Loops of Wire. An armature may be formed by interconnecting four loops of wire and four commutator segments. The connections are shown in Fig. 19. Each loop has its terminals connected to adjacent commutator segments. The brushes must be broad enough to bridge the insulation between adjacent segments, and they are mounted on the commutator in such a position that they short-circuit the loops when the sides of the loops are moving parallel to the magnetic field.

An inspection of Fig. 19 will assist you in understanding the following statements. When the armature is in the position shown in Fig. 19, the e.m.f. induced in the loops *A* and *C* is zero, and the e.m.f. induced in the loops *B* and *D* is a maximum. Of course, loops *A* and *C* are short-circuited by the brushes, but no damage results, as there is no e.m.f. induced in these loops in this position. Loops *B* and *D* are connected in parallel between the brushes, and the e.m.f. between the brushes is that induced in either loop *B* or *D*, which is supposedly the same. Now, as the armature rotates from the position shown in Fig. 19, the e.m.f. in loops *B* and *D* decreases in value and the e.m.f. in the

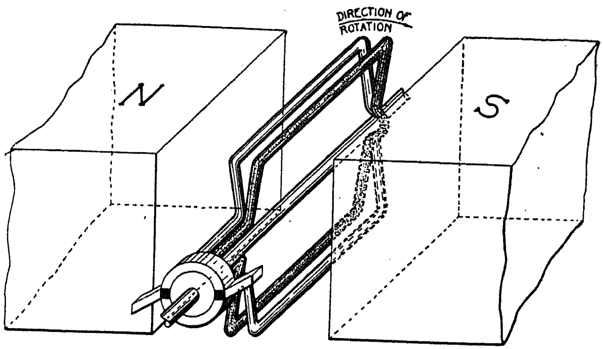


Fig. 18 Direct-Current Generator Composed of Two Loops of Wire and a Commutator of Two Segments

loops *A* and *C* increases in value, starting with zero. A small angular rotation of the armature results in the short-circuit of the loops *A* and *C* being removed, and the loop *A* is connected in series with the loop *B* and likewise the loop *C* is connected in series with the loop *D*. This connection remains while the armature rotates for one-fourth revolution, when the loops *B* and *D* are short-circuited by the brushes and the loops *A* and *C* are in parallel between the brushes. During this one-fourth revolution the e.m.f. induced in loops *B* and *D* decreased in value from a maximum to zero value, as shown by the curve *bd* in Fig. 20, and the e.m.f. induced in the two loops *A* and *C* has increased in value from zero to a maximum value, as shown by the curve

ac in Fig. 20. The e.m.f. between the brushes is the sum of the e.m.f.'s and it is represented by the heavy curve in Fig. 20. The maximum value of this e.m.f. occurs when the loops are making an angle of 45 degrees with the position shown in Fig. 19, or they have turned one-eighth turn from the starting point. The e.m.f. in all the loops is the same for this position of the armature and is equal to 0.707 of the maximum e.m.f. The total e.m.f. between the brushes is equal to twice this value, since two loops are in series, or it is equal to 1.414 times the maximum e.m.f. that can occur in any one of the loops. The e.m.f. between the brushes will fluctuate between the maximum value occurring in a single loop and 1.414 times this maximum value. With a four-loop armature there will be four of these pulsations for each

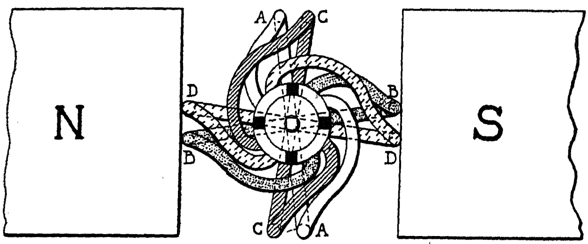


Fig. 19. Direct-Current Generator Composed of Four Loops of Wire and a Commutator of Four Segments

revolution. As the number of loops and segments is increased the amount of this fluctuation is decreased, but the number of fluctuations per revolutions is increased.

Open- and Closed-Circuit Armature Windings. In an open-circuit winding the different loops do not as a whole form a closed circuit, but each loop is in circuit only when the commutator segments to which it is connected are in electrical contact with the brushes. The windings shown in Figs. 14 and 16 are of the open-circuit type.

A closed-circuit winding is one in which the loops forming the winding are interconnected and form one or more closed circuits upon themselves, and each loop is always in circuit except when it is short-circuited by the brushes. The winding shown in Fig. 19 is of the closed-circuit type.

Practically all modern armatures are of the closed-circuit type. Open-circuit armatures have been used to some extent in

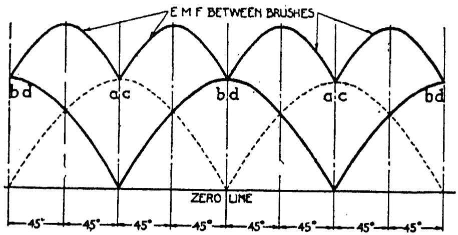


Fig. 20. Curve Representing Variation in Value of Electromotive Force between Brushes of Direct-Current Generator Shown in Fig. 19

series arc-lighting generators and quite extensively in alternating-current machines.

ARMATURE WINDINGS FOR DIRECT-CURRENT MACHINES

TYPES OF ARMATURES

Classification. Armatures, considered as a whole, may be divided into three classes according to the shape of the core upon which the winding is placed and the manner in which the winding is placed on the core. These three classes are:

Ring armatures
Drum armatures
Disc armatures

Ring Armatures. Ring armatures were first used by Pacinotti in 1860, but they are commonly known by the name of Gramme, the French electrician, who reintroduced them in 1870. Gramme wound the wire around the entire surface of the annular core, which was made of varnished iron wire in order to reduce the losses due to eddy currents. Pacinotti wound the wire between projecting teeth upon an iron ring, as shown in Fig. 21.

In ring windings the parts of the windings which pass through the inside of the ring do not cut any magnetic lines (assuming

there is no magnetic flux passing across the opening inside of the iron ring), and, as a result, are inoperative, so far as the e.m.f. of the machine is concerned.

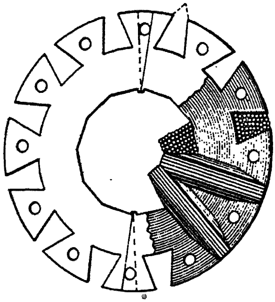


Fig. 21. Partially Completed Ring-Wound Armature

An armature of the Gramme ring type is shown in Fig. 22. Some of the machines of this type were so designed as to have the outside of the ring act as a commutator, the current being collected directly from the winding by brushes which trailed on the periphery of the ring, while the inner part of the conductors cut the magnetic lines. A complete Gramme ring armature provided with a commutator of the usual form is shown in Fig. 23.

Drum Armatures. Drum armatures were first introduced by Siemens, who wound coils of iron wire upon a frame of nonmagnetic material. Armatures of this type in their complete form were first brought out in 1871 by Von Hefner Alteneck, and improved later by Weston and others. The principle of the drum winding is shown in Fig. 24, and it is apparent that it is much simpler than the ring winding. Each wire is placed on the outside of the drum, usually parallel to the axis of the armature core, and is connected to another wire by means of connecting wires called end-connections, which do not pass through the core. The only reason for having any opening in the core at all, other than to save the material, is to improve the ventilation and cooling of the armature. In two-pole machines the end-connections run across the ends of the core and connect wires which are almost diametrically opposite. In multipolar machines the end-connections join wires which are separated by a distance

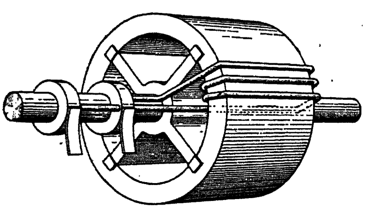


Fig. 22. Simple Gramme Ring Winding

approximately equal to the distance between corresponding points on adjacent poles, so that the electrical pressures in the wires thus connected will act in the same direction around the loop.

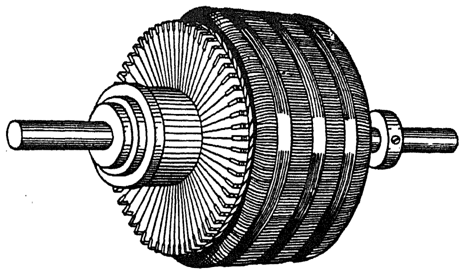


Fig 23 Couple Gramme Ring Winding

The drum armature may be thought of as derived from the ring armature by moving the inner connections of the winding, or the part of the winding on the inside of the ring, to the outer surface, at the same time stretching the coil so that the two sides will occupy approximately corresponding positions under adjacent poles.

Disc Armatures. The disc armature differs from the other two, in that the wires in which the electrical pressure is induced instead of being on the outer cylindrical surface of the armature

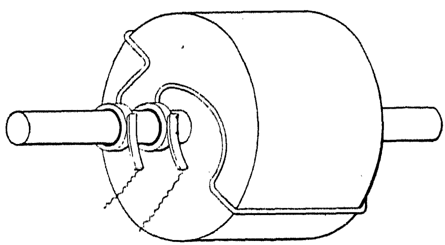


Fig. 24. Principle of Simple Drum Winding

core, are placed radially on the flat sides of a disc. The principle of the disc armature is shown in Fig. 25.

Discussion of Different Types. The drum armature is used more than either of the others in the construction of modern

machines. The ring armature is seldom used, and the disc armature is practically obsolete. The principle of operation of the drum armature is practically the same as that of the ring armature, but since the ring armature is not nearly so common as the drum armature, most of the following treatment on armatures for direct-current machines relates specifically to drum armatures.

Some Disadvantages of Ring Armatures. In developing or placing a ring winding in place on the armature core it usually is necessary to thread the wire through the hollow, cylindrical core; this necessitates bending the conductor back and forth. This winding operation must be carried on by hand. Since the

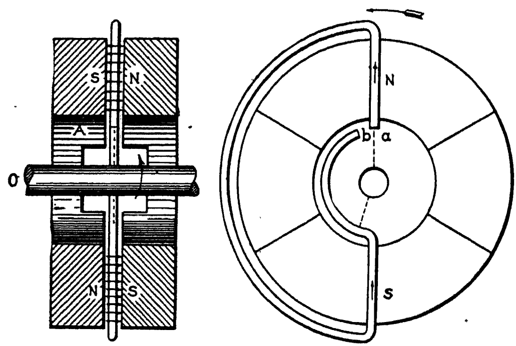


Fig 25. Principle of Disc Armature

wire forming the winding must be bent to conform to the armature core, it is very difficult to wind an armature that requires a wire of large size. It is practically impossible to prevent the insulation on the wire being damaged during the process of winding, and the extra amount of care that must be taken means that more time is required.

Ring Windings Difficult to Hold in Position. Only one-half of each turn or loop has an e.m.f. induced in it, and as a result more wire is required; this means additional expense. However, the resistance of the armature is greater, owing to the increased amount of wire in each of the circuits through the armature winding.

Some Advantages of Drum Armatures. Since all the loops or coils for a certain armature are of the same shape and size, they may be wound on forms. Such coils, called form-wound coils, in some cases may be made with automatic machinery. The economy resulting from this type of construction is very obvious. In form-wound coils it is possible to use wire of almost any size. The insulation on the wire is not subject to any great amount of abuse in winding a form-wound coil. The armature winding may be rigidly held in position by being placed in the armature slots provided in the surface of the armature core. Binding wedges or binding wires keep the winding from being thrown out of the slots by centrifugal force when the armature rotates.

ARMATURE CONSTRUCTION

Purpose of Armature Core. The function of the armature core is two-fold: it supports the armature winding and it carries the flux from one pole core to the adjacent pole cores; that is, it completes the magnetic circuit between the pole pieces. On account of its high permeability and great strength, iron is by far the best material for armature cores. Armature cores may be of annular, ring, cylindrical, or disc form. The cylindrical form is used on small machines, the annular on large machines, so that the cooling surface is larger and the weight of material is reduced. It has been seen, however, that when a mass of iron (or other conductor) is rotated in a magnetic field, wasteful eddy currents are set up in the mass; hence solid cores of metal should on no account be used in any armature. In order to reduce these currents as much as possible, it has become the practice to build up armature cores of thin, soft iron or mild steel discs, insulated from one another by varnish, rust, or paper. These discs are arranged to have their planes *parallel* to the direction of the flux and *perpendicular* to the flow of eddy currents. An armature core composed of such sheets, forced together by hydraulic or screw pressure, is found to be from 85 to 95 per cent iron, the remainder of its volume being made up of insulation, air space, etc.

Core Bodies. The cores of armatures are made of laminae (thin discs) of wrought iron or mild steel. These discs are stamped out of sheet metal, and range from 0.014 inch to 0.025

inch in thickness, the former thickness being that most often used at the present time. Core discs up to about 30 inches in diameter are punched in one piece, while larger diameters are

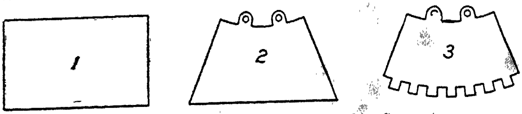


Fig. 26. Order of Stamping Armature Core Segments

stamped out in sections, Fig. 26, and the core built up as indicated in Fig. 27, alternating the joints. These stampings are now so accurately made that, after assembling the discs into a core, the slots need not be milled out, as was formerly necessary. Milling is most objectionable because it burrs over the edges of the discs. The burrs thus produced connect adjacent discs and facilitate the flow of eddy currents, thereby defeating the purpose of lamination. Turning after assembling also tends to increase the iron losses. Hence, if it is found that the periphery of the core body is irregular, it should be ground true.

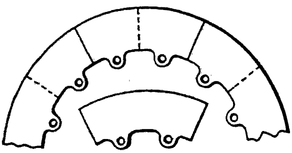


Fig. 27 Method of Building up Armature Core from Segments

The core discs are insulated from each other either by a thin coating of iron oxide on the discs or by a thin coating of japan varnish. Sometimes shellac or paper is used for insulating these laminae; but on account of the greater expense and the fact that the efficiency is only slightly bettered, these latter are applied only in special cases.

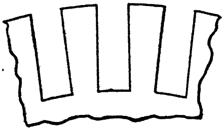


Fig. 28. Armature Teeth with Parallel Slots

Shapes of Armature Teeth. The armature cores used in practice are almost always provided with a toothed surface. Thus the armature winding is protected, the length of the air gap reduced, and the winding is prevented from slipping in the core. The general efficiency of the machine is greater than when a smooth core is used. The number of teeth must be relatively

large, about four per inch of armature diameter, to prevent noise and excessive eddy-current losses in the pole faces. A common form of armature tooth is slightly narrower at the root than at

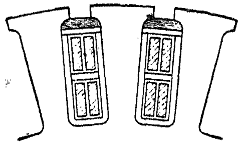


Fig. 29. Teeth with Projecting Tops

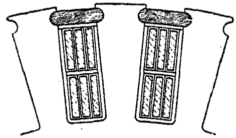
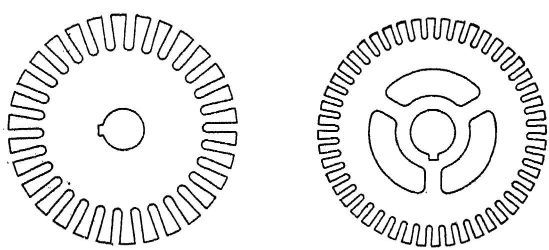


Fig. 30. Notched Teeth to Hold a Wedge

the top, the resulting slot having parallel sides, Fig. 28. Fig. 29 illustrates a form in which the tops are slightly extended to give a larger magnetic area at the top, thus decreasing the reluctance of the air gap and helping to retain the inductors in the slots by the insertion of a wedge of wood. The latter object is also attained by notching the teeth as in Fig. 30, in case it is not desirable to increase the area of the top of the tooth.

Binding-Wire Channels. In machines using binding wires to hold the armature inductors in the slots, it is usual to stamp some of the core discs of slightly reduced diameter so that the binding wires may be flush with the surface of the armature. The reduction is seldom more than $\frac{1}{4}$ inch on the diameter, giving a channel not more than $\frac{1}{8}$ inch deep. The width is determined by the number and the size of the binding wires.



Figs. 31 and 32. Forms of Armature Core Discs for Small Machines

Mounting of Core Discs. Some mechanical means must be provided to hold the core discs together, and to connect them rigidly to the shaft. In the case of small cores not exceeding

15 inches in diameter, the core discs take either of the forms shown in Figs. 31 and 32, the latter being preferable on account of increased ventilation. The laminae are simply keyed to the shaft, being held together under heavy pressure by end-plates of cast steel or cast iron, which are in turn pressed inward either by nuts fitting in threads upon the shaft or by bolts passing through, but insulated from the armature discs and end-plates.

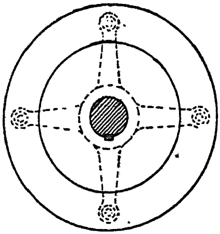


Fig. 33 Core Discs Bolted to Spider—Bolts Pass through Discs

Large cores in which the discs are made in sections, or for which the material of the core near the shaft is not required, are built upon an auxiliary support called a spider, which has different forms, depending on the mode of attachment between it and the core discs. Fig. 33 shows the discs held together and to a skeleton pulley, or spider, by bolts passing through them, the spider being keyed to the shaft. The objection to this construction is that the bolt-holes reduce the effective area of the core, thus strangling the magnetic flux. This difficulty may be overcome by placing the bolts internal to the core, as in Fig. 34, in which case they need not be so well insulated. Another and newer arrangement provides the discs with dovetail notches or extensions which fit into extensions or notches on the spider arms, Fig. 35. The sectional view shows the method of holding the laminae together by means of bolts and end-plates, also the R extensions for supporting the end-connections of a barrel winding.

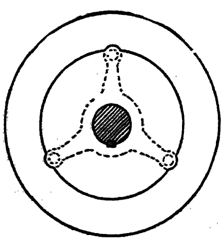


Fig. 34. Core Discs Bolted to Spider—Bolts Placed Inside of Discs

The hubs of armature spiders are usually cleared out between their front and back bearing surfaces to facilitate fitting the shaft; and in larger sizes the seating on the shaft is often turned to two different sizes to admit of easier erecting, Fig. 36. Figs. 37 and 38 show a spider and other features of construction of a

large machine. The rim of the spider is cut in six pieces, each of which has four dovetail notches. If it is cast in one piece, trouble may arise from unequal strains in the metal due to contraction.

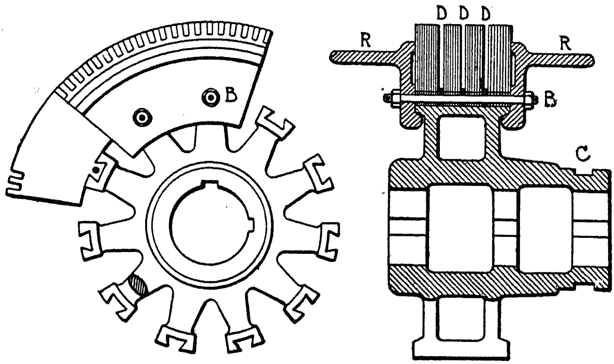


Fig 35 Method of Mounting Large Armature Core on Armature Spider

Ventilating apertures are provided, and on the side of each arm, Fig. 37, are seen the seatings and bolt-holes for attaching the commutator hub and the rim which supports the winding. In Fig. 38, which shows a completed core, the supporting rim and narrow ventilating ducts are visible. Figs. 39 and 40 show two views of a completely assembled armature core and commutator ready for the winding; the armature spider is shown in Fig 41 An armature core (in the process of construction) for a revolving armature is shown in Fig. 42, and a core (also in the process of construction) for a stationary armature, as used in alternating-current machines, is shown in Fig. 43.

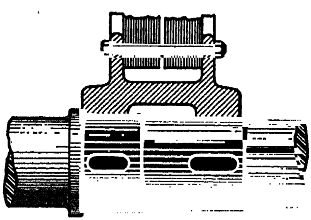


Fig. 36. Construction of Armature Hub

A completed armature core for a small machine is shown in Fig. 44.

Ventilating Ducts. Armature cores heat from three causes, namely, hysteresis, eddy-currents in the iron, and I^2R losses in

the copper inductors. In order that the temperature-rise of the armature shall not exceed a safe figure (60° C), it is necessary in the large and heavy-duty types to resort to means of ventilation, usually ducts which lead the air out between the core discs. To keep the core discs apart at these ducts, it is necessary to introduce distance pieces, or ventilators. Fig. 45 illustrates some of these devices. At *A* are shown simple pieces of brass riveted radially at intervals to a special core disc 0.04 to 0.05 inch thick.

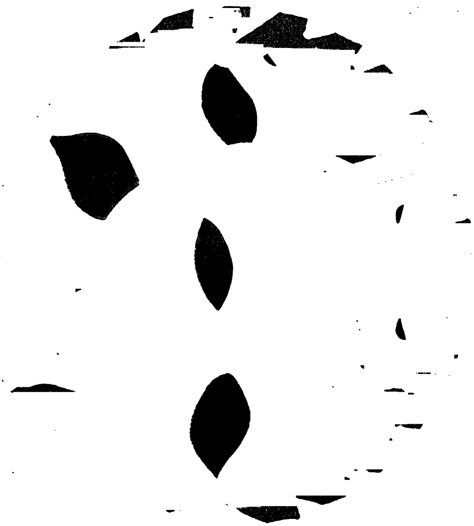


Fig. 37 Armature Spider for Large Generator

This form fails to provide adequate support for the teeth, a difficulty obviated in the form shown at *B*, which has, behind each tooth, a strip of brass about 0.4 inch wide set edgewise. This strip is cast with or brazed to a special casting of brass riveted to a stout core disc. In a recent construction, shown in Fig. 46, the core plate next to the duct is ribbed, affording good support for both the core and teeth of the next plate.

Binding Wires. With toothed-core armatures the inductors may be held in the slots by wedges of wood, as already stated, or

by bands of wire wound around the armature. These binding wires must be strong enough to resist the centrifugal force which tends to throw the armature inductors out of the slots, and yet must occupy as little radial space as possible, in order not to interfere with the clearance between the armature and the pole pieces. The common practice is to employ a tinned wire of hard-drawn brass, phosphor bronze, or steel, which, after the winding, can be sweated together by solder into one continuous band.

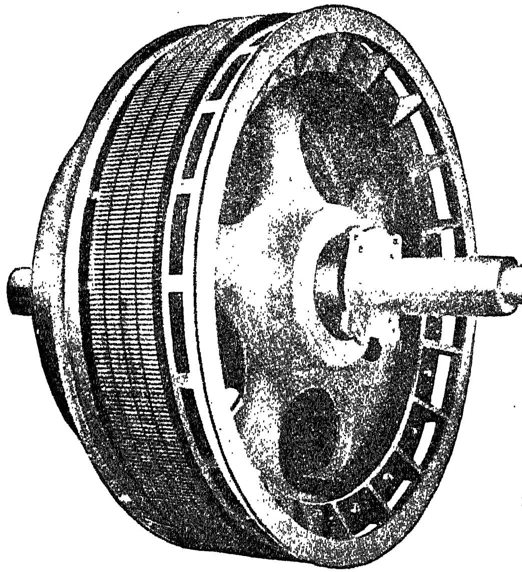


Fig. 38. Armature Core and Commutator Mounted on Temporary Shaft

Under each belt of binding wire a band of insulation is laid, usually consisting of two layers: first, a thin strip of vulcanized fiber or of hard red varnished paper slightly wider than the belt of wire, and then a strip of mica in short pieces of about equal width. Sometimes a small strip of thin brass, with tags which can be turned over and soldered down, is laid under each belt of binding wire to prevent the ends of the binding wires from flying out.

To estimate the proper size and number of binding wires required, assume that d is the diameter (in inches) of the circular path described by a mass of weight W_1 pounds, and the

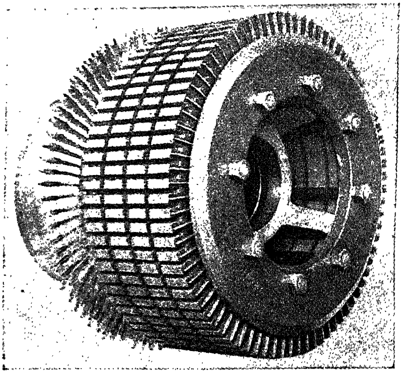


Fig. 39. Completely Assembled Armature and Commutator Ready for Winding (Rear View)
Courtesy of General Electric Company

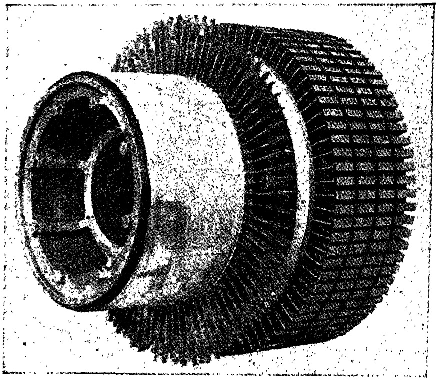


Fig 40 Completely Assembled Armature Core and Commutator Ready for Winding (Front View)
Courtesy of General Electric Company

centrifugal force will be $=0.0000143 \times d \times W_1 \times \overline{\text{r.p.m.}}^2$ pounds weight. So that if we assume a value of 100,000 pounds per square inch as the maximum allowable tensile stress in steel or phosphor-

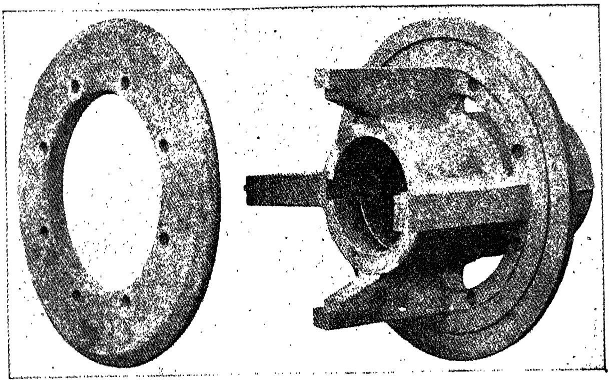


Fig. 41 Armature Spider for Armature Shown in Figs 39 and 40
Courtesy of General Electric Company

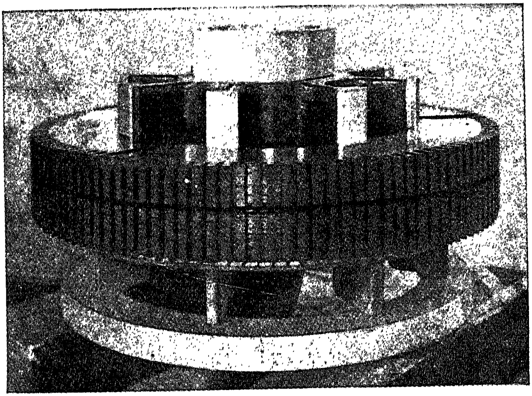


Fig. 42 Armature Core for Revolving Armature in Process of Construction
Courtesy of Allis-Chalmers Company

bronze wire, and allow a safety factor of, say 10, the total section of binding wire required will be equal to

$$\frac{0.0000143\times 10\times W\times N\times d\times \overline{\text{r.p.m.}}^{2}}{\pi\times 100{,}000}$$

or $$4.55\times 10^{-10}\times W\times N\times d\times \overline{\text{r.p.m.}}^{2}\ \text{sq. in.,}$$

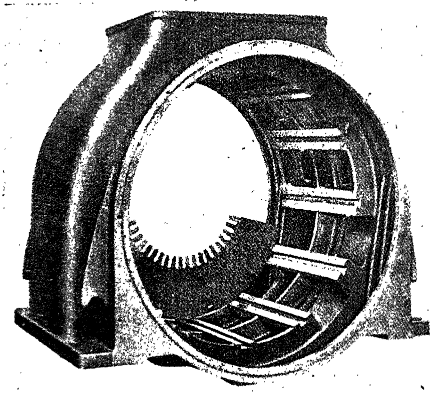


Fig. 43. Armature Core for Stationary Armature in Process of Construction
Courtesy of Allis-Chalmers Company

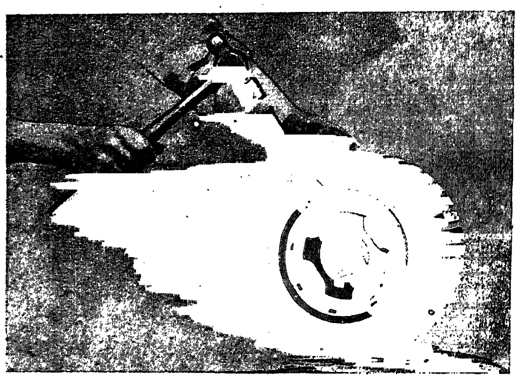


Fig 44 Complete Armature Core for Small Direct-Current Machine
Courtesy of Reliance Electric and Engineering Company

in which W is the weight of one inductor, and N the number of inductors; consequently W_1 will be equal to WN. From this total necessary section and an appropriate wire table, the number of wires is calculated, and they are then arranged in suitable belts.

Example. Let $W=0.39$ lb.; $N=1536$; $d=62$ in.; r.p.m. $=150$. The total necessary section computed by the above formula is 0.379 square inch. Referring to the wire gage tables, we find that 148 wires of No. 15 B.& S. gage will fulfill the conditions. These may be arranged as follows: 5 belts of 16 wires each over the core body, and 4 belts of 17 wires each over the extended ends of the winding (that is, 2 belts of 17 wires each over each end).

Wedges. In the cases where wedges are driven into grooves in the teeth to close up the slot, the usual material employed is a well-baked hardwood, such as hornbeam or hard, white, vulcanized fiber.

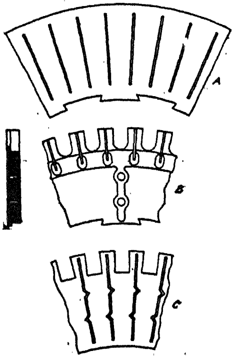


Fig. 45. Different Types of Distance Pieces or Ventilators

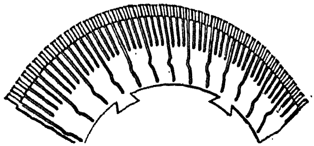


Fig. 46. Ribbed Core Plate Used in Forming Ventilating Ducts

COMMUTATOR AND BRUSH CONSTRUCTION

Commutator Bars. Commutator bars are almost always made of copper; other metals, such as brass, iron, or steel, are not satisfactory on account of pitting and burning. Rolled copper is preferable, because of its toughness and uniform texture; but in some cases, on account of the shapes necessitated by different methods of connection to the armature conductors and various clamping devices, the segments are either cast or drop-forged, the latter being at present the commercial type.

In order to secure a good fit, the cross-section of the bars should be properly tapered according to the number of segments that makes up the whole circumference. It is obvious that if the number of segments equals 360, each segment plus its insulation (on one side) should have a taper of 1 degree; while if the number

TABLE I

Thickness of Commutator Insulation

Voltage of Machine	Thickness of Mica	
	Between Neighboring Segments	Between Segments and Shell and between Segments and Clamping Device
Less than 150	0.020 to 0.03 in.	0.06 to 0.10 in.
Less than 300	0.025 to 0.04 in.	0.08 to 0.13 in.
Less than 1000	0.04 to 0.06 in.	0.10 to 0.16 in.

of segments equals 36, the taper would be 10 degrees. It is not practicable, however, to use mica insulation that has not parallel faces; hence the segment is tapered, and any defect in the taper of the latter cannot be made good with insulation. It is found, however, that when the number of segments exceeds 150, bars of the same taper can be used in constructing a commutator having either two more or two less than the designed number.

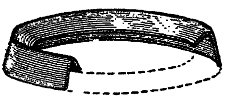


Fig. 47. End Insulating Ring of Commutator

Insulation. It is important to have good insulation between each bar and its neighbor, and especially good insulation between the bars and the sleeve or hub around which they are mounted, as well as between the bars and the clamping devices that hold them in place, since the voltage between bars is not as great as that between the bars and the metal-work of the machine. It is essential that the insulating material be such that it will not absorb oil or moisture; hence, asbestos, plaster, and vulcanized fiber are inadmissible. The end insulation rings may be of micanite, or, if for low voltage, of that preparation of paper pulp known as press-board or press-spahn. The conical rings, used to insulate the dovetails on the bottom of the bars from the hub, are usually built of micanite molded under pressure while hot. Fig. 47 illustrates such an end-ring, cut away to show its section.

Commutators using air gaps between the segments as insulation have been tried; but, excepting in the case of arc-lighting machines where the segments are few in number and the air gap large, they have not proved successful, owing to the difficulty of keeping the gaps free from metallic dust.

It is of importance that the mica selected for insulating the bars from one another should be soft enough to wear away at the same rate as the copper bars, and not project above the segments. Amber mica, soft and of rather cloudy color, is preferred to the harder clear white or red Indian variety. The usual thicknesses are as given in Table I.

Commutator Construction. For small machines two common constructions are shown in Fig. 48. The commutator segments are secured between a bushing or hub and a clamping ring, the

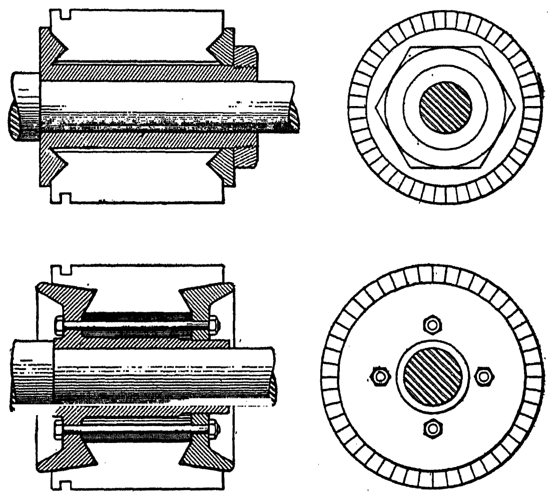


Fig. 48. Common Method of Commutator Construction for Small Machines

latter being mounted on the hub, and forced to grip the bars by means of a nut on the hub or by bolts passing through the ring and hub, as in Fig. 49. The ends of the bars are beveled so that the ring and bushing draw the segments closer together on tightening.

The hub in small machines is usually of cast iron keyed to the shaft; but in large machines the commutator is built upon a strong flange-like support or shell, bolted to the armature spider, Fig. 50, or mounted on a separate spider secured to the shaft, Fig. 51,

When drawn copper strip is used, the design should be such that the available surface for the brushes takes up nearly the whole length of the bar, and the beveled ends should be as simple as possible. With drop-forged segments this is not so important.

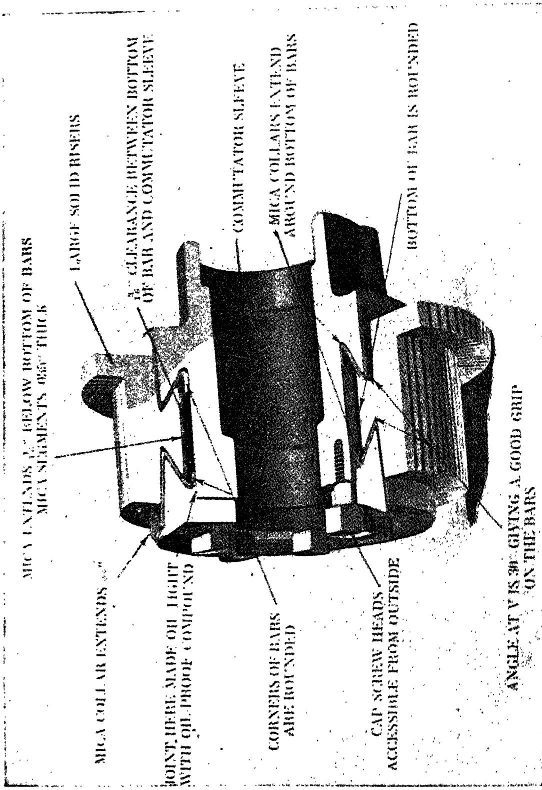


Fig. 49. Commutator for Small Machine Cut Away to Show Construction
Courtesy of Reliance Electric and Engineering Company

In building commutators it is usual to assemble the bars to the proper number, with the interposed pieces of mica, clamping them temporarily around the outside with a strong iron clamp, as

shown in Figs. 52 and 53, or forcing them into an external steel ring under hydraulic pressure. They are then put into a lathe and the interior surface is bored out, after which the ends are

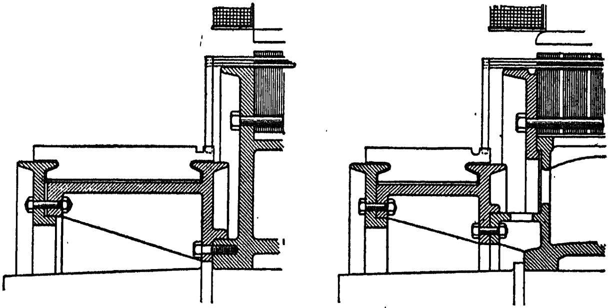


Fig. 50. Commutator Construction for Large Machines. Commutator Spider is Bolted to Armature Spider

turned up in such a way that the angular hollows will receive the clamping pieces. The whole is then mounted with proper insulation upon the sleeve, and the clamping end-pieces are screwed up. It is then heated and the clamps still further

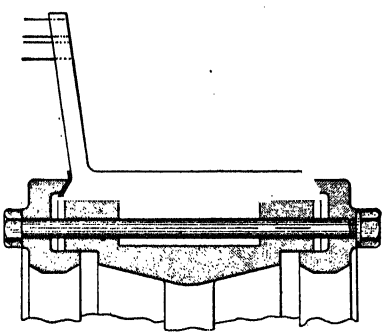


Fig. 51. Commutator Construction for Large Machines. Commutator Spider Is Mounted on Armature Shaft Independent of Armature Spider

tightened up, after which the temporary clamp or ring is removed and the external surface turned up. The commutator shell or spider and clamping ring for a large commutator are shown in

Fig. 54, and the mica insulating rings for same are shown in Fig. 55. Two completed commutators are shown in Figs. 56 and 57.

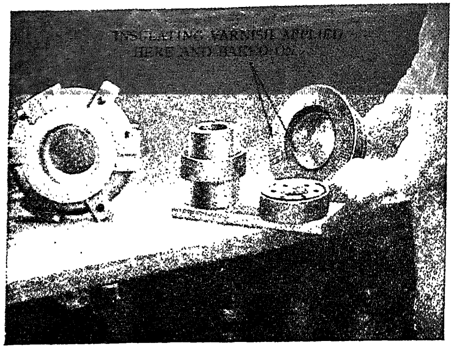


Fig. 52. Method of Constructing and Forming Small Commutator
Courtesy of Reliance Electric and Engineering Company

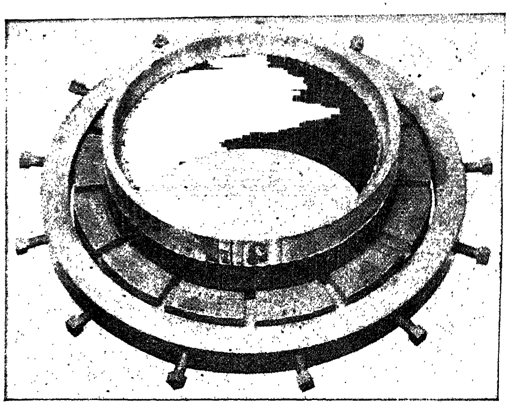


Fig. 53. Method of Constructing and Forming Large Commutator
Courtesy of General Electric Company

Commutator Risers. Connection is made with the armature inductors by means of radial strips or wires, sometimes called

risers, which are inserted into a cut at the corner of each bar and firmly held there by a screw clamp and solder. Figs. 58, 59, and 60 illustrate various modes of making connection to the commu-

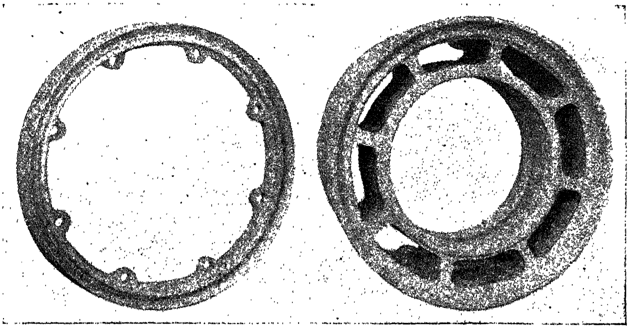


Fig. 54. Commutator Shell or Spider and Clamping Ring for Large Commutator Shown in Fig. 53
Courtesy of General Electric Company

tator bar. The risers are connected to the armature winding in several different ways as indicated in Fig. 61. In some evolute windings no risers are needed, the ends of the evolute being fastened directly to the commutator bars. Similarly, in the case

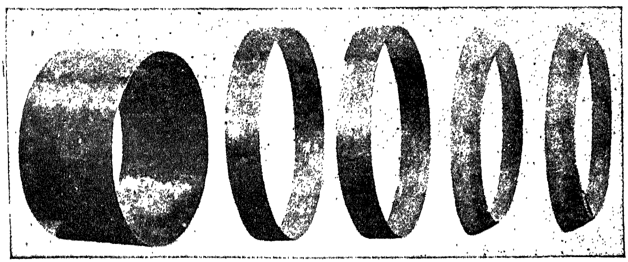


Fig. 55. Mica Insulating Rings for Commutator Shown in Fig. 53
Courtesy of General Electric Company

of barrel-wound armatures, no risers are needed if the commutator diameter is very nearly that of the armature.

Brushes and Brush-Rigging. Carbon brushes are almost the only type that is now considered. Their shape depends upon the

type of brush-holder selected, and upon whether the brushes are applied to the commutator radially or at an angle. Fig. 62

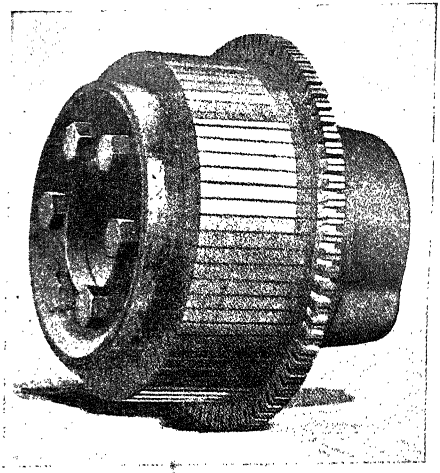


Fig. 56. Completed Commutator for Small Machine
Courtesy of Reliance Electric and Engineering Company

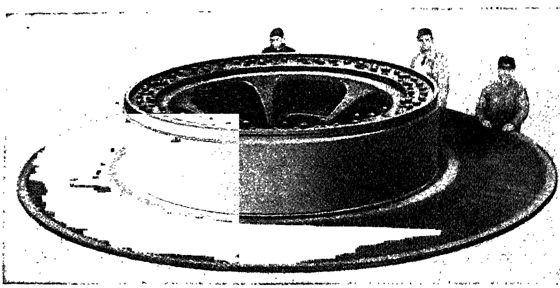
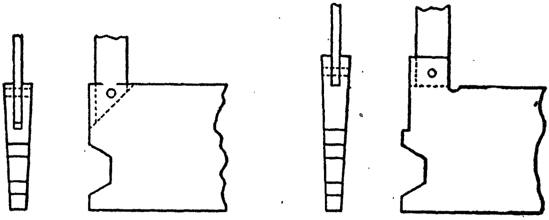


Fig. 57 Completed Commutator for Very Large Machine
Courtesy of Allis-Chalmers Manufacturing Company

illustrates various shapes. The mechanism for holding the brushes must fulfill the following requirements:

(1) The brushes must be held firmly against the commutator, but allowed to follow any irregularity in the contour of the latter without jumping away.



Figs. 58 and 59. Methods of Connecting Commutator Risers to Commutator Bars

(2) The mechanism must permit the brushes to be withdrawn while the commutator is rotating, and must feed them forward as required.

(3) Spring pressure must be adjustable, and the spring must not carry current.

(4) The springs must not have too great inertia, or they will not readily fulfill the first condition in regard to following the commutator.

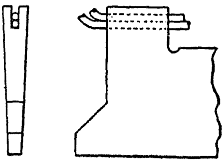


Fig. 60. Armature Winding Connected Directly to Commutator Bar

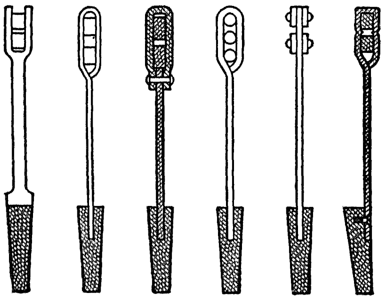


Fig. 61. Methods of Connecting Armature Winding to Commutator Risers

(5) Insulation must be very thorough.

(6) The mechanism must be so arranged that the position of the brushes may be shifted.

(7) All parts must be firm and strong, so the brushes will not chatter as the result of vibration while the machine is running.

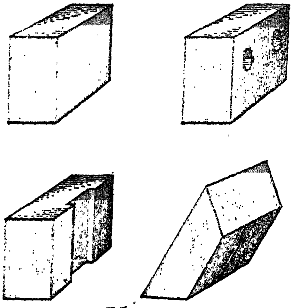


Fig. 62. Several Different Forms of Carbon Brushes

The commercial forms of holders for carbon brushes may be classified under three types: hinged structures, parallel spring holders, and reaction holders.

Fig. 63 illustrates a hinged brush-holder, and an arm holding several. The carbon moves in a light frame, being held against the commutator by a spring whose tension may be adjusted. Connection is made between the brush and the arm by means of a flexible lead, tinned and laid in a slot in the upper part of the carbon. A metal cap placed over the top and sweated in place makes a permanent contact. This is shown by the two illustrations of the brush.

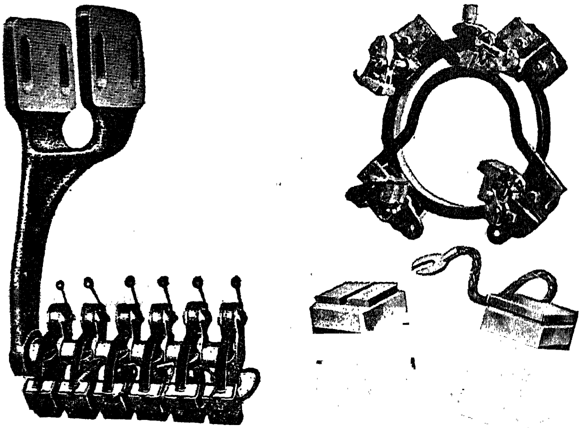


Fig. 63. Brush Rigging and Hinged Brush-Holder

Fig. 64 illustrates a parallel-movement type. The brush is held firmly in the holder by a clamping screw, and the whole arrangement is pressed against the commutator by a pressure

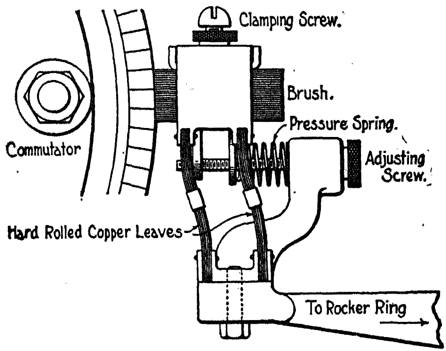


Fig. 64. Parallel-Movement Type of Brush-Holder

spring, whose tension may be varied by means of the adjusting screw. Connection is made between the brush and the stationary part of the holder by means of two sets of rolled-copper leaves which at the same time act as flexible joints.

In Fig. 65 is shown a reaction type of brush-holder. The brush C is pressed against the commutator by the adjustable spring L, the holder B being secured firmly to the rocker arm P by means of the set-screw q. The brush is furnished with a dovetail-shaped groove along its entire inner edge, and into this groove is fitted a screw in the face of the holder B.

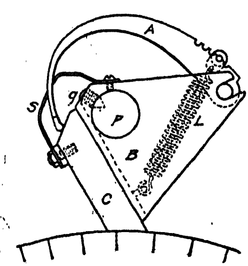
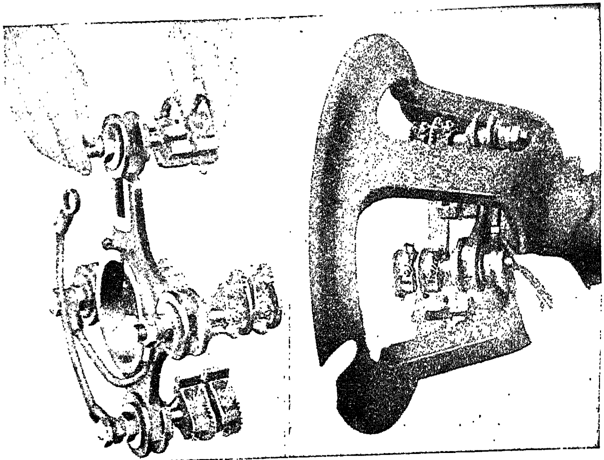


Fig. 65. Reaction Type of Brush Holder

Rockers and Rocker Arms. For small machines the rocker arm is usually clamped upon a shoulder turned upon the bearing pedestal as indicated in Figs. 66 and 67. For large multipolar generators, the rocker arms, that is, the rods on which the brush-holders are held, are fixed at equidistant points around a cast-iron rocker ring, which is itself



Figs. 66 and 67. Brush Rocker Arm for Small Machine and Method of Mounting Same on Bearing Pedestal

Courtesy of Reliance Electric and Engineering Company

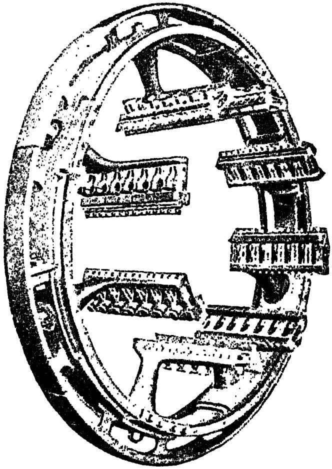


Fig. 68. Rocker Ring and Brush Mounting

supported on brackets projecting from the magnet yoke. This construction is shown in Fig. 68.

DEVELOPMENT OF THE E.M.F. EQUATION FOR A DIRECT-CURRENT GENERATOR

Analysis for One Inductor. Fundamentally the e.m.f. induced in an armature winding depends upon the rate at which the inductors composing the winding are cutting the magnetic lines, and the number of these inductors that are connected in series. Let us first consider the value of the e.m.f. induced in a single inductor as it revolves in the magnetic field or the field revolves with respect to it, as the case may be. If the magnetic lines that enter or leave each of the magnetic poles be represented by the symbol ϕ, and the number of poles by the letter p, then each inductor will cut $p \times \phi$ magnetic lines with each revolution. Now if the inductor and the magnetic field make r.p.s. revolutions per second, then each inductor will cut $p \times \phi \times$r.p.s. magnetic lines in one second.

Total E.M.F. The manner in which the total number of inductors is connected will determine the number that are connected in series. The magnetic lines cut by one inductor multiplied by the number of inductors in series gives the value of the magnetic flux cut by one path or circuit, and this result divided by 10^8 will give the value of the average e.m.f. induced in the armature winding. If the total number of inductors on the armature be represented by N, and these inductors are so connected that there are several paths, or circuits, through the armature in passing from the negative terminal of the machine through the armature winding to the positive terminal, then the number of inductors in series in any one of these paths or circuits will be equal to the total number of inductors divided by the number of paths or circuits. The number of paths or circuits through an armature winding, usually represented by the letter a, depends upon the kind of winding and the number of poles. This will be discussed in detail later.

The above statements may be combined and all written in the form of an equation as follows:

$$\text{E.M.F.} = \left(\frac{N}{a} \times p \times \phi \times \text{r.p.s.}\right) \div 10^8,$$

in which E.M.F. is electromotive force induced in the armature winding; N is total number of inductors on the armature; a is number of paths or circuits through the armature winding; p is number of poles in field structure; ϕ is magnetic lines per pole; r.p.s. is revolutions per second; and 10^8 is number of lines that must be cut per second in order to induce an e.m.f. of one volt.

Examples. 1. An armature winding for a four-pole generator has 188 inductors and these inductors are connected in such a manner that there are two circuits or paths through the winding from the negative to the positive terminal of the machine. If the armature is rotated at 1050 revolutions per minute and there are 167,000 magnetic lines per pole, what e.m.f. will be induced in the winding?

Solution.

$$N=188;\ a=2;\ p=4;\ \phi=167{,}000;\ \text{and r.p.s.}=1050\div 60=17.5$$

Substituting these values in the equation for the e.m.f. gives

$$\text{E.M.F.}=\frac{188\times 4\times 167000\times 17.5}{2\times 10^8}$$

$$=\frac{21\,977\,000\,000}{2\times 10^8}$$

$$=109.88 \text{ volts}$$

2. If the armature in the above example is rotated at a speed of 1575 r.p.m., what change must be made in the number of magnetic lines per pole in order that the e.m.f. generated in the armature winding will remain the same?

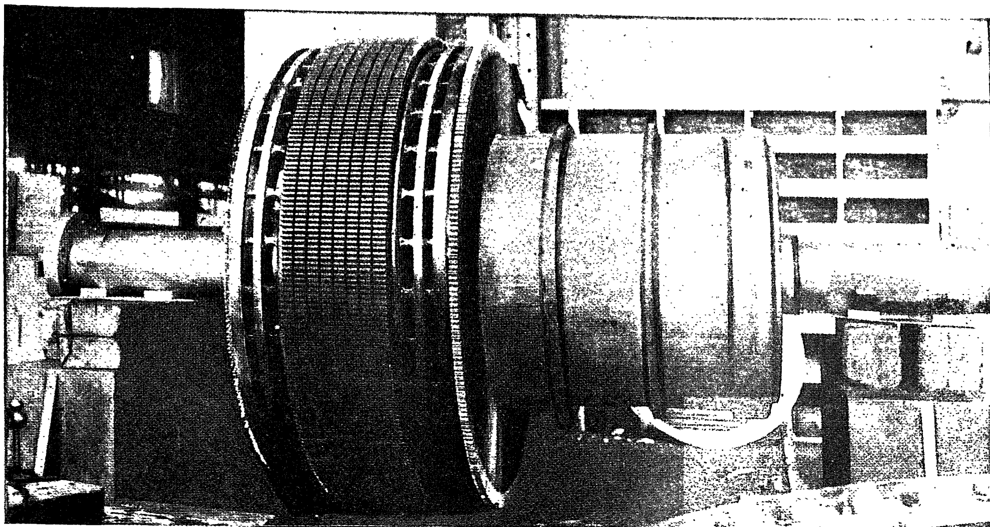
Solution. It is obvious from an inspection of the equation giving the value of the e.m.f., that the induced e.m.f. will increase directly as the speed; that is, if the speed is doubled the e.m.f. will be doubled, and if the speed is reduced to one-half of its original value the e.m.f. will be reduced to one-half of its original value, assuming all the other quantities in the equation remain constant in value. Likewise if the magnetic lines per pole be increased or decreased in value there will be a corresponding increase or decrease in the value of the induced e.m.f., assuming all other quantities in the equation remain constant in value. Now if the speed of the armature of a machine is increased there must be a decrease in the value of the magnetic lines per pole in order that the e.m.f. may remain constant in value. Thus, if the speed is increased to twice its original value, then the magnetic lines per pole must be reduced to one-half their original value, etc.

In this particular case the speed is increased to $1575\div 1050$ or $\frac{3}{2}$ of its original value, so that the magnetic lines must be decreased to $\frac{2}{3}$ of their original value in order that the induced e.m.f. shall remain constant in value.

3. If the winding in example 1 above be changed so that there are four paths or circuits rather than two, and all other conditions remain the same, what will be the value of the induced e.m.f.?

Solution. Changing the winding from a two-circuit to a four-circuit winding decreases the number of inductors in series in any one path to one-half of the previous value, assuming, of course, that the total number of inductors remains the same. A reduction in the value of the number of inductors in series results in a reduction in the value of the induced e.m.f., and the reduction in the value of the induced e.m.f. will be in proportion to the reduction in the number of inductors in series. In this particular case the number of inductors in series is reduced to one-half of its previous value.

The above statements are clearly shown by the e.m.f. equation. Since the value of the number of circuits appears in the denominator of the equation, an increase in its value will result in a decrease in the induce e.m.f., and likewise a decrease in the number of circuits will result in an increase in the e.m.f., assuming all other quantities in the equation remain constant in value.



ARMATURE CORE AND COMMUTATOR FOR 3000 K.W. DIRECT-CURRENT GENERATOR
Courtesy of Allis-Chalmers Company, Milwaukee, Wisconsin

ARMATURE WINDING

PART II

ARMATURE WINDINGS FOR DIRECT CURRENT MACHINES—Continued

DESIGN OF WINDINGS

Ring and Drum Windings. In designing the armature winding for a direct-current generator or motor, the number of armature inductors is determined by means of the fundamental e.m.f. equation. The real problem is, then, the interconnecting of the various inductors in such a way that their individual e.m.f.'s will add together to produce the required total e.m.f., and in such a manner that the armature winding as a whole will be at all times symmetrical with respect to the brushes and magnetic poles. Three distinct types of closed-coil armature windings are shown in Figs. 69, 70, and 71. These windings are all for a four-pole machine. There are 24 inductors in the windings shown in Figs. 69 and 70, and 26 inductors in the winding shown in Fig. 71.

The winding shown in Fig. 69 is a ring winding, while the windings shown in Figs. 70 and 71 are drum windings. The arrangement of the two drum windings may be made clearer by resorting to the use of what are called developed diagrams, as shown in Figs. 72 and 73. The developed diagrams might be thought of as being derived from Figs. 70 and 71 by rolling out the cylindrical surface of the armature core into a plane, and at the same time stretching the commutator segments so that they remain in the same relative position with respect to the inductors composing the winding.

Winding Element. Each of the windings shown in Figs. 69, 70, and 71 consist of a number of identical elements, and one of these elements is shown in heavy lines in each of these figures. An element of an armature winding is that portion of the winding, which, beginning at a commutator segment, ends at the next commutator segment encountered in tracing through the winding. An

element in its simplest form consists of a single inductor in the case of a ring winding, as shown in Fig. 69, and in the case of a lap and wave winding it consists of two inductors, as shown in Figs. 70 and 71.

In the case of the ring winding, the number of inductors in an element is equal to the number of turns, while in a lap and wave

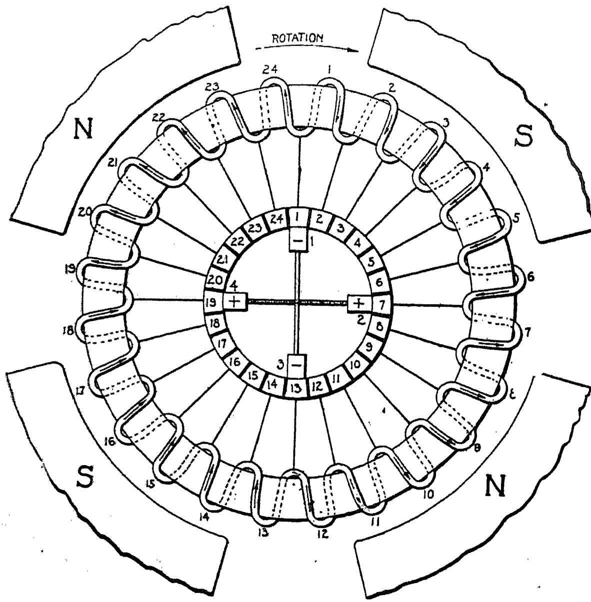


Fig 69 Ring-Wound Armature for a Four-Pole Machine

winding the number of inductors in an element is equal to twice the number of turns in the element.

Small armatures that are designed to operate on relatively high voltages may have as many as five turns in an element; but in large machines there is, as a rule, only one turn per element so as to improve commutation. Keeping the turns in the elements low reduces the self-induction, and hence there is less opposition

to the reversal of the current during commutation. The coefficient of self-induction varies as the square of the number of turns.

Ring, Lap, and Wave Windings. The three windings shown in Figs. 69, 70, and 71 belong, respectively, to the ring, lap, and wave types of closed-circuit windings. The origin of the terms

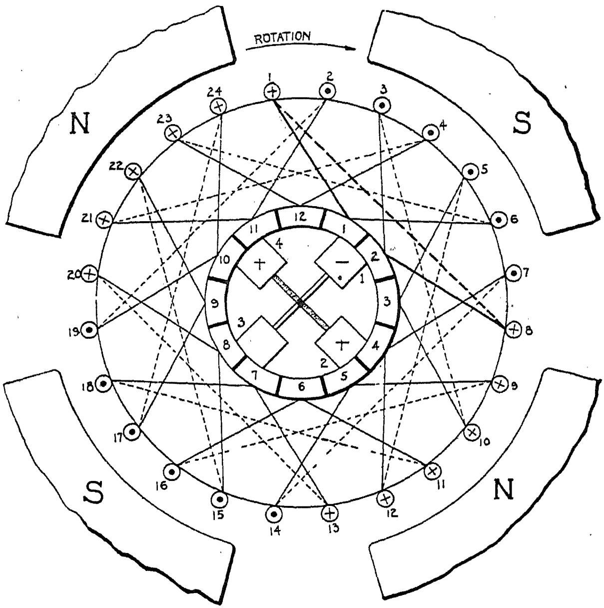


Fig 70 Lap-Wound Drum Armature for a Four-Pole Machine

lap and wave will be quite evident from an inspection of Figs. 72 and 73.

Lap Winding. In tracing through the winding shown in Fig. 72, you advance around the armature core in one direction at the back end of the armature, the end away from the commutator, and around the core in the opposite direction at the front end of the armature. In other words, the winding laps back on itself and for this very reason it is called a lap winding.

Wave Winding. In tracing through the armature winding shown in Fig. 73, you advance around the armature core in the same direction at both the back and front ends of the core in a wave fashion, and for this reason the winding is called a wave winding. Lap and wave windings are frequently referred to as parallel and series windings respectively.

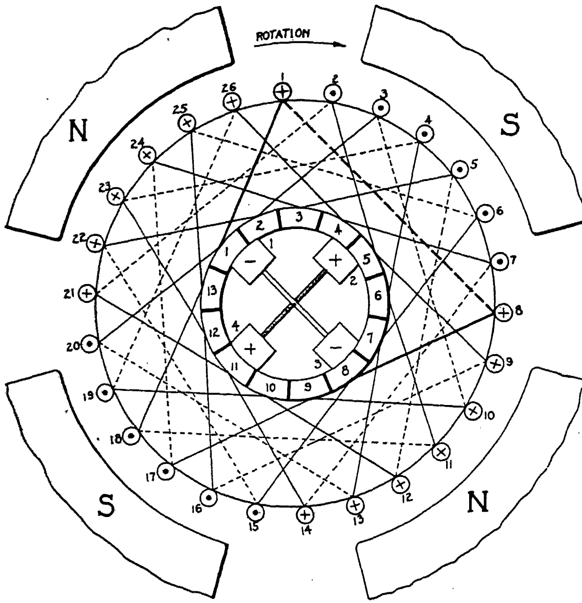


Fig. 71. Wave-Wound Drum Armature for a Four-Pole Machine

Figs. 72 and 73 show that the two sides of an element are under the inductive influence of two adjacent magnetic poles of opposite polarity and the e.m.f.'s induced in the two sides of an element are in opposite directions across the surface of the armature. The e.m.f.'s in the two sides of an element, however, act in the same direction around the element for practically all positions of the element and the e.m.f. between the terminals of an element is equal to the sum of the e.m.f.'s in series composing the element.

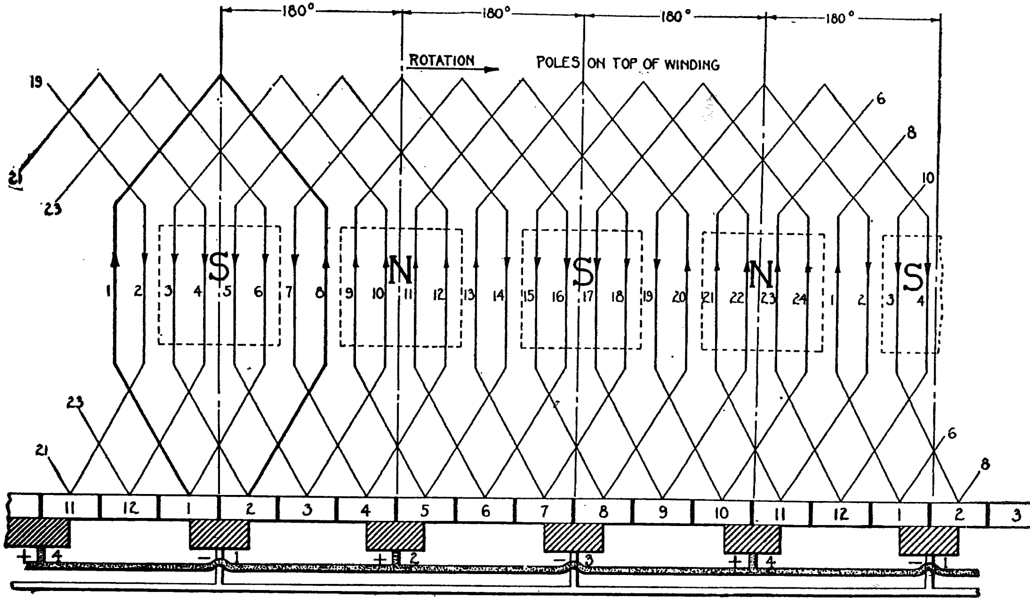


Fig. 72. Developed Diagram of Lap Winding Shown in Fig. 70

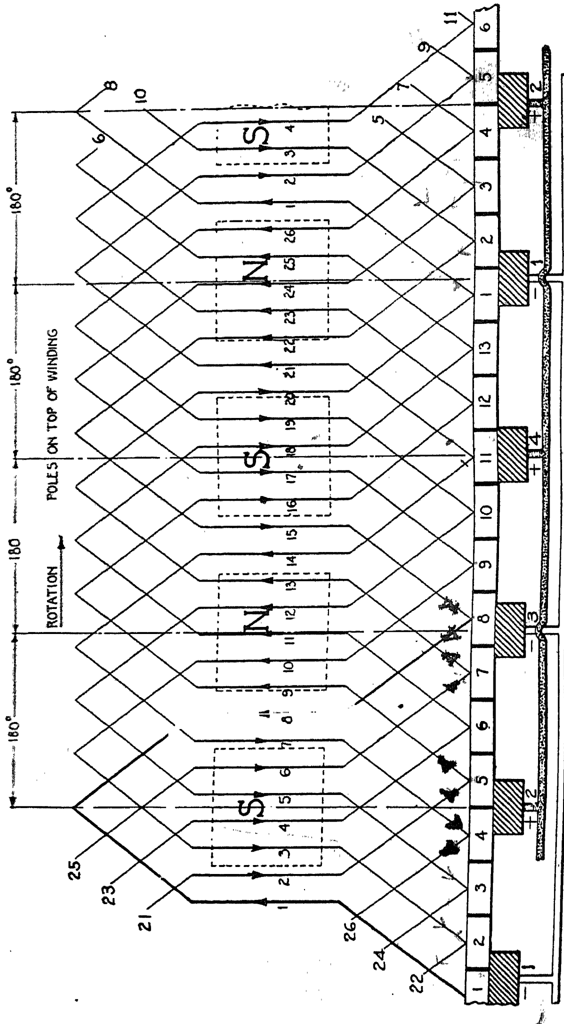


Fig. 73. Developed Diagram of Wave Winding Shown in Fig. 71

In the simple lap winding shown in Fig. 72 the terminals of the element are connected to adjacent commutator segments, while in the case of the simple wave winding shown in Fig. 73 the terminals of an element are connected to commutator segments which are approximately a double-pole pitch apart. The pole pitch is the distance between corresponding points on adjacent magnetic poles.

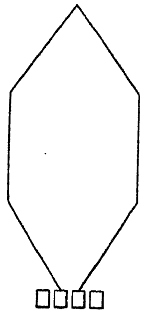


Fig. 74. Element for Lap Winding Composed of a Single Turn

An element for a lap winding, composed of a single turn is shown in Fig. 74, and one composed of two turns is shown in Fig. 75. Two elements for a wave winding are shown in Figs. 76 and 77.

Tracing Circuits. An examination of the windings shown in Figs. 69 and 70 will show that there are four circuits through the winding from the negative brushes to the positive brushes. The two negative brushes are connected together and form one terminal of the armature winding as a whole, while the two positive brushes are connected together and form the other terminal. In the case of a generator the direction of current through the armature winding is from the negative terminal to the positive terminal. The position of the brushes on the commutator is such that they short-circuit the elements, when the resultant e.m.f. induced in the inductors forming the element is a minimum This, however, is not always the case on account of commutation requirements, as will be explained later The inductors composing the winding are numbered consecutively from one up to the total number, in this case twenty-four

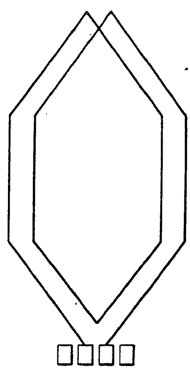


Fig. 75. Element for Lap Winding Composed of Two Turns

The four circuits through the winding shown in Fig. 69 may be traced as follows: Starting with the negative brush marked *1* and tracing through inductors *1*, *2*, *3*, *4*, *5*, and *6* you arrive at the positive brush *2*. A second circuit may be traced from the negative

brush *1* through inductors *24, 23, 22, 21, 20,* and *19* to the positive brush marked *4.* A third circuit may be traced from the negative brush marked *3,* through the inductors *12, 11, 10, 9, 8,* and *7* to the positive brush marked *2,* and a fourth circuit may be traced from the negative brush marked *3* through the inductors *13, 14, 15, 16, 17,* and *18* to the positive brush marked *4.* The width of the brushes shown in Fig. 69 is equal to the width of a commutator segment, and the position of the winding in the field, as shown in the figure, is such that no elements are short-circuited by the brushes. Just an instant after that represented in the figure four elements will be short-circuited by the brushes. In practice the brushes must be made wider than a commutator segment.

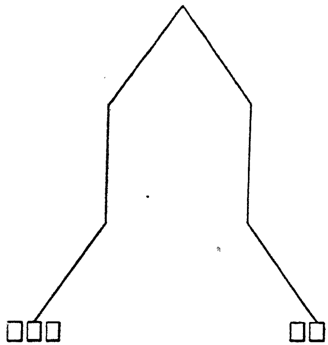


Fig. 76. Element for Wave Winding Composed of a Single Turn

The four circuits of the winding shown in Figs. 70 and 72 may be traced in a manner similar to the above, and the inductors composing each circuit determined. Starting with the negative brush marked *1* you may pass through inductors marked *3, 10, 5,* and *12* before you arrive at a positive brush, in this case the positive brush marked *2.* A second circuit may be traced from the negative brush marked *1,* through the inductors *6, 23, 4,* and *21* to the positive brush marked *4.* A third circuit may be traced

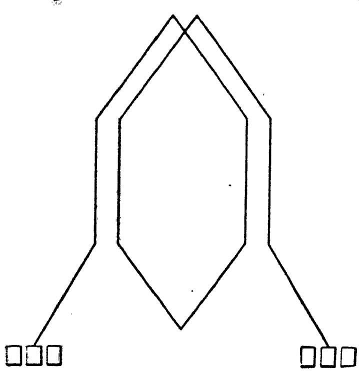


Fig. 77. Element for Wave Winding Composed of Two Turns

from the negative brush marked *3* through inductors marked *18, 11, 16,* and *9* to the positive brush marked *2*. And a fourth circuit may be traced from the negative brush marked *3* through the inductors, *15, 22, 17,* and *24* to the positive brush marked *4*.

The position of the winding in Figs. 70 and 72 is such that four elements are short-circuited by the brushes, since each brush is resting on two commutator segments. Brush *1* is short-circuiting an element composed of inductors *1* and *8*. Brush *2* is short-circuiting an element composed of inductors *7* and *14*. Brush *3* is short-circuiting an element composed of inductors *13* and *20,* and brush *4* is short-circuiting an element composed of inductors *19* and *2*. The inductors that are short-circuited by the brushes will change as the armature rotates, as can be seen by an examination of Figs. 70 and 72.

The circuits through the winding shown in Figs. 71 and 73 may be traced as follows: Starting with the negative brush marked *1* and tracing through inductors *1* and *8* you arrive at a commutator segment which is under a negative brush, so that the element composed of inductors *1* and *8* is short-circuited by the two negative brushes marked *1* and *3,* which are connected together. Tracing on through the winding from the negative brush marked *3,* you pass through inductors *15* and *22,* which are short-circuited by brushes *1* and *3,* and then through inductors *3, 10, 17, 24, 5, 12, 19,* and *26,* and you arrive at a segment under the positive brush marked *2,* thus completing one circuit through the winding. Continuing from brush *2,* you pass through inductors *7* and *14* which are short-circuited by the two positive brushes, marked *2* and *4,* then through inductors *21* and *2,* which are short-circuited by the two positive brushes marked *2* and *4,* then through inductors *9, 16, 23, 4, 11, 18, 25,* and *6* to the negative brush marked *3,* thus completing a second circuit through the winding. Tracing on through the winding from the negative brush marked *3* you pass through inductors *13* and *20,* which are short-circuited by the two negative brushes, marked *1* and *3* back to the starting point, or segment number *1* to which inductor number *1* is connected.

Brushes Required for Lap Winding. Since the current in an element must undergo commutation each time the element passes through the neutral zone of the magnetic field, that is the position in

which the resultant induced e.m.f. is zero, it follows that the element may be short-circuited by a brush or brushes at each such position, and not interfere to any great extent with the e.m.f. between the terminals of the machine. The number of neutral zones each element passes through in one revolution is equal to the number of magnetic poles in the field structure of the machine, hence the number of permissible brush sets may in all cases be the same as the number of poles. In all ring and lap windings, such as those shown in Figs. 69 and 70, it is imperative that as many brush sets be provided as there are magnetic poles. Let us assume that one of the brushes in Fig. 69 is removed, say the positive brush marked *2*, and then trace the circuits through the armature winding. The two circuits on the left-hand side of the armature will not be disturbed, that is, the circuits from negative brush *1* to positive brush *4* and from negative brush *3* to positive brush *4*. Removing positive brush *2* results in two of the circuits being connected in series between the two negative brushes, and since the induced e.m.f. in the two circuits acts in a direction away from the negative brushes and they are equal in value, it follows that the resultant induced e.m.f. in the circuit connecting the two negative brushes on the right-hand side of the armature winding is zero. The removal of the positive brush results in one-half of the armature winding being inoperative, so far as the external circuit to which the armature is connected, is concerned. The removal of any one of the brushes will result in the same conditions of affairs for a four-pole machine.

The same results will be obtained if any one of the brushes in Figs. 70 and 72 be removed. In general, the removal of any one of the brushes from the commutator of a lap- or ring-wound armature results in all the inductors under one pair of poles becoming inoperative so far as the external circuit is concerned. Thus, in a six-pole machine if one of the brushes is removed from the commutator, one-third of the inductors become inoperative, in an eight-pole machine one-fourth of the inductors become inoperative when one of the brushes is removed, etc. The removal of the single brush does not prevent the armature from operating; but it reduces the current capacity of the armature, because the number of circuits in parallel through the winding is reduced.

If two of the brushes, say brushes marked *2* and *3* in Fig. 69, be removed, the armature will still operate but not up to its full capacity, as explained above. In this case there will be one circuit from the negative brush marked *1* to the positive brush marked *4*, and a second circuit from the negative brush *1* around the right-hand side of the armature to the positive brush *4*. The circuit around the right-hand side of the armature is composed of the inductors under three different poles while the circuit direct from brush *1* to brush *4* is composed of the inductors under only one magnetic pole. The e.m.f. in the circuit on the right-hand side is a combination of three e.m.f.'s and each of these is the sum of the e.m.f.'s induced in the inductors under each of the three magnetic poles. Two of these e.m.f.'s oppose each other and the third acts in a direction from the negative brush *1* to the positive brush *4*, so that the resultant e.m.f. in the right-hand circuit is numerically the same as the e.m.f. in the circuit direct from brush *1* to brush *4*.

Resistance of Circuits. The resistances of the two circuits from brush *1* to brush *4* are not the same, as the one on the right-hand side is composed of three times as many inductors as the one on the left-hand side. As a result of this difference in the resistance of the two circuits in parallel between brush *1* and *4*, the two circuits will not carry the same current when the armature is delivering current to the external circuit; but the left-hand circuit will carry approximately three times as much current as the right-hand circuit, because its resistance is approximately one-third as great.

Brushes for Wave Winding. In a wave winding, although as many brushes as there are poles may be used, two brushes will be sufficient irrespective of the number of poles. Thus in Fig. 71 any one of the positive brushes may be removed if a negative brush is removed at the same time. Assuming that brushes *2* and *3* are removed then brushes *1* and *4* will continue to operate and there will be no change in the number of circuits through the armature winding. A careful inspection of Fig. 73 will make it clear why two brushes instead of four are sufficient to collect the current; for it will be observed that the ~~positive~~ brushes *1* and *3* are connected not only by the external conductor but also by

elements which are in or near the neutral zone, and they are, therefore, equivalent to additional conductors joining the positive brushes; hence the heavy external connection and one of the positive brushes may be omitted. Likewise, the external connection between the negative brushes and also one of the negative brushes may be omitted. This relation holds for any number of poles, and all the brushes may be removed except one positive and one negative and the armature will continue to operate with the same number of circuits through the winding.

When two of the brushes in Figs. 71 and 73 are removed, the remaining brushes short-circuit two of the elements in series. If the machine were six-pole and all the brushes were removed except two, one positive and one negative, each brush would short-circuit three elements in series. The short-circuiting of several elements in series results in poorer commutation than is obtained when each element is short-circuited by itself, which is the case when there are as many brushes as there are poles.

The current-carrying capacity of two sets of brushes is not always sufficient to take care of the total capacity of the machine, and in such cases it is necessary to use more brushes.

Position of the Brushes. It is interesting to note that the position of the brushes in the case of the ring winding is midway between the poles, and in the case of the lap- and wave-wound drum windings the position of the brushes is in the center of the poles. With the brushes in these positions on the commutator, the length and form of the two end-connections of each element is approximately the same. The position of the brushes, however, can be changed by changing the relative position of the commutator segments and the elements, when the armature is being wound, or by reconnecting the elements to the segments. Good commutation will require the brushes to be moved slightly in the direction of rotation in the case of a generator and in the opposite direction in the case of a motor from the position they occupy in Figs. 69, 70, and 71.

Distribution of Lap and Wave Windings. In the case of the lap winding, all the inductors in each of the several circuits are under the influence of the same two magnetic poles, while in the case of the wave winding the inductors in the different circuits are

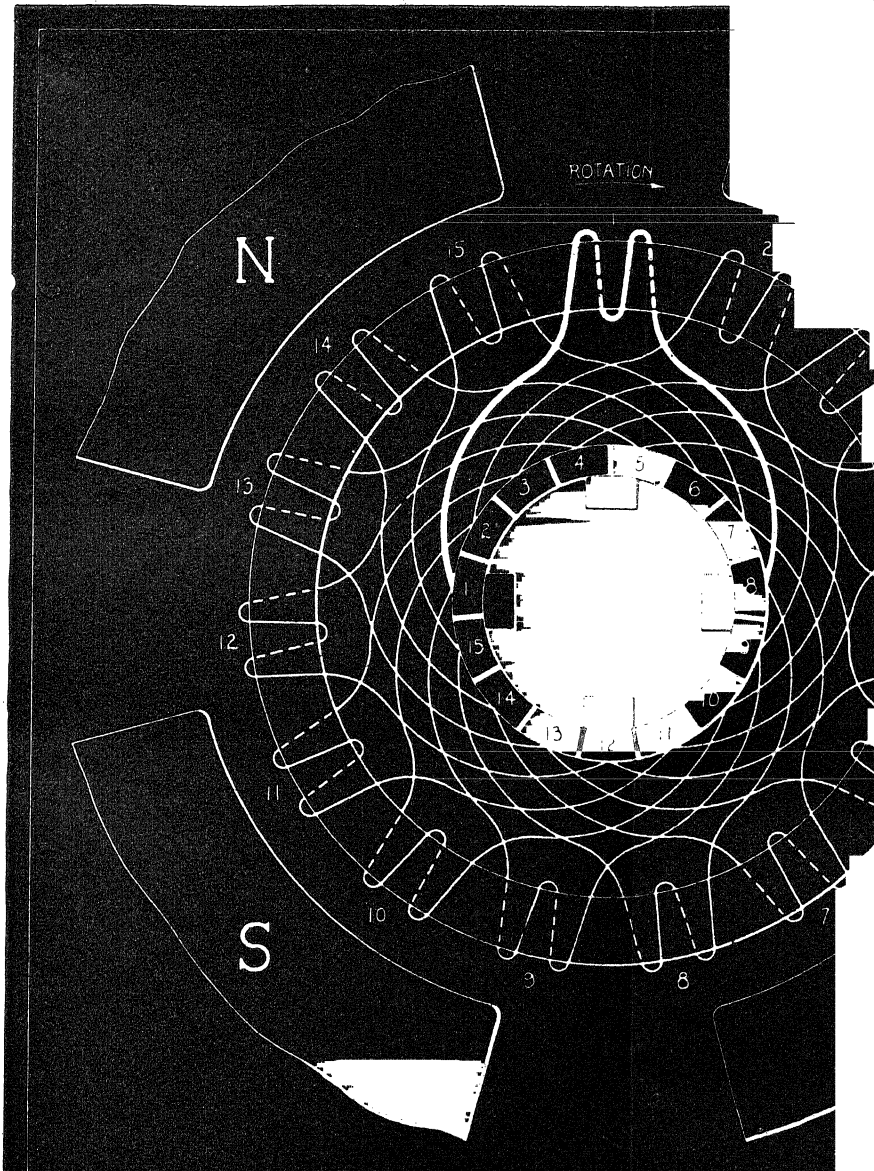


Fig. 78. Wave-Wound Ring Armature for a Four-Pole Machine

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distributed around the armature under all of the magnetic poles. Any variation in the magnetic flux under the different magnetic poles will result in the electromotive force in the different circuits in the case of a lap winding being unequal, while in the wave winding all of the different circuits will have the same e.m.f. induced in them, since they are all affected alike by the unequal flux distribution. The unequal e.m.f.'s in the different circuits that are connected in parallel will result in there being a current through the winding, even though the armature may not be supplying any current to the external circuit. The presence of these currents results in a needless heating of the armature winding, and hence a reduction in the efficiency of the machines.

Current and Voltage Relations for Lap and Wave Windings. The number of inductors in series in each of the circuits in the case of the wave winding, as shown in Figs. 71 and 73, is greater than the number of inductors in series in each of the circuits in the case of the lap winding shown in Figs. 70 and 72, and as a result the e.m.f. induced in each circuit of the wave winding will be approximately twice as great as is induced in each circuit of the lap winding, since the number of inductors in series in each circuit of the wave winding in Fig. 73 is approximately twice as great as the number of inductors in series in each circuit of the lap winding in Fig. 72. Wave windings as a rule are used for machines of relatively high voltage, and lap windings for machines of comparatively low voltage. The current capacity of the lap winding shown in Fig. 70 is just twice as great as the current capacity of the wave winding shown in Fig. 71, assuming the same size wire is used in each of the windings. Since the power output of the armature in watts is equal to the product of the voltage and current, it follows that the power the two armature windings shown in Figs. 70 and 71 are capable of delivering will be approximately the same.

Wave-Wound Ring Armature. A wave-wound ring armature for a four-pole machine is shown in Fig. 78, and a development of the winding is shown in Fig. 79. The winding is composed of 15 elements and 15 commutator segments, and four brushes are shown. Elements *1* and *8* are short-circuited by the positive brushes, for the position of the armature as shown in the figure. The positive

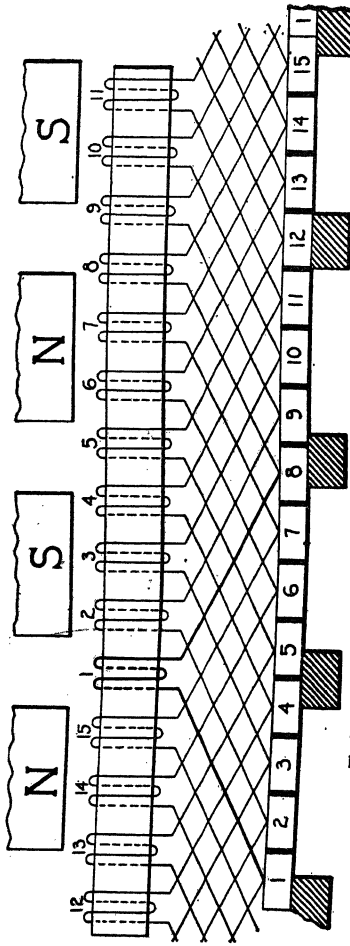

Fig. 79. Developed Diagram for a Wave-Wound Ring Armature for a Four-Pole Machine

brushes are the ones on the right- and left-hand side of the commutator as shown in Fig. 78. Elements *5* and *12* are short-circuited by the negative brushes just at the instant represented in the figures.

Simplex and Multiplex Windings. Two bipolar ring-wound armatures are shown connected in parallel in Fig. 80, and the combined current output of these two armatures, assuming they are identical, is equal to twice the capacity of either machine alone. Exactly the same results may be obtained by placing the

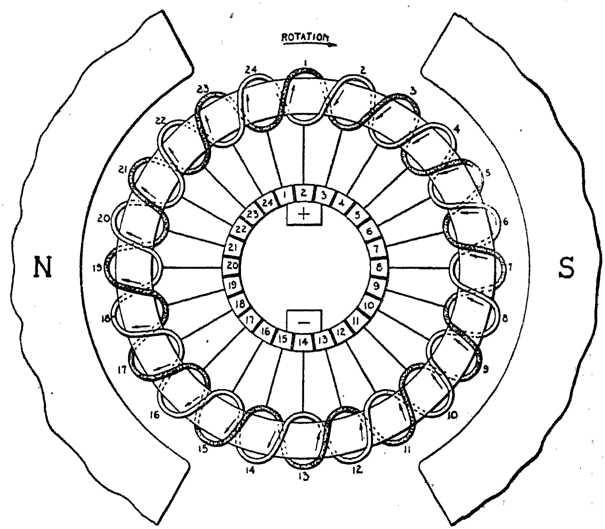

Fig. 81. Duplex Armature Winding Composed of Two Independent Windings

two windings on a single armature core, Fig. 81. Here the two windings are electrically independent of each other, except for the connection between the segments that is made by the brushes. The commutator segments of the two windings are "sandwiched," or imbricated, and there are just twice as many segments in the commutator shown in this figure as there are in each of the commutators shown in Fig. 80. A winding of the form shown in Fig. 81 is called a duplex winding as distinguished from each of

the simplex windings shown in Fig. 80. This multiplication of simplex windings may be used in forming what are called triplex, quadruplex, etc., windings. In general, windings of this kind are spoken of as multiplex windings.

Drum windings of both the lap and wave types may be treated in exactly the same manner as the ring windings described above. It must be borne in mind that the brushes in the case of a multiplex winding must be broad enough to bridge sufficient segments so that the brushes are always in electrical contact with each of the several windings.

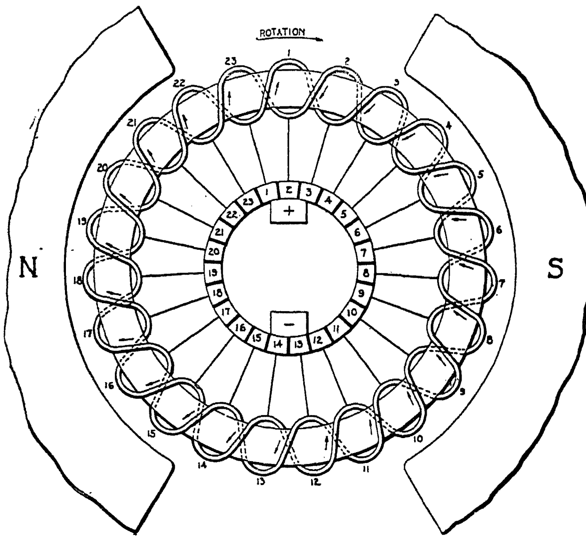

Fig. 82. Duplex, Singly Re-entrant Ring Armature for a Two-Pole Machine

Singly Re-entrant Winding. Suppose that one of the elements and one of the commutator segments shown in Fig. 81 is omitted and that the remaining 23 elements are equally spaced around the armature and connected to the commutator segments as shown in Fig. 82. In Fig. 81 there are two independent windings, but in Fig. 82 all the various elements are interconnected. An inspection

with inductor *2*. A winding of this kind, in which there are two independent closures, is said to be doubly re-entrant.

Trebly Re-entrant Winding. A triplex ring armature for a two-pole machine is shown in Fig. 83. The twenty-four inductors are connected in such a manner that there are six circuits through the armature winding between the brushes. The winding is trebly re-entrant because there are three independent closures.

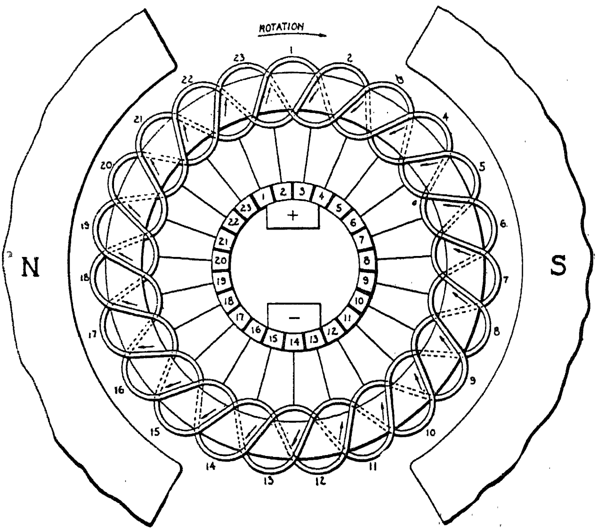

Fig. 84. Triplex, Singly Re-entrant Ring Armature for a Two-Pole Machine

Triplex Winding, Singly Re-entrant. The winding shown in Fig. 84 is of the triplex singly re-entrant type. It has one element less and one commutator segment less than the winding shown in Fig. 83. It is triplex because there are three times as many circuits through it as there are in the case of a simplex winding, and it is singly re-entrant because there is only one closure.

It is thus seen that the multiplicity and re-entrancy of a winding can be carried to any extent that is desired, but it is very seldom that the multiplicity or re-entrancy exceeds three.

In the above discussion, a ring type of winding was used on account of its simplicity, and it should be borne in mind that all the conclusions apply equally well to lap and wave windings, as will be pointed out in the various examples of armature windings.

General Design Considerations

Winding Pitch. It will be observed in Fig. 72 that the back end of half-element number *1* is connected to the back end of half-element number *8*, and the front end of half-element number *8* is connected to the front end of half-element number 3. The difference in the numbers of the half-elements is called the winding pitch. When this difference is taken at the back end of the armature it is called the back winding pitch; it is represented by Y_1. When the difference is taken at the front end of the armature it is called the front winding pitch; it is represented by Y_2. In tracing through any armature winding diagram it is customary to consider the clockwise direction around a circuit or element as positive. In Fig. 72 the back pitch is $8-1$ or $+7$, and the front pitch is $3-8$ or -5. In Fig. 73 the back winding pitch is $8-1$ or $+7$, and the front winding pitch is $15-8$ or $+7$.

Commutator Pitch. The numerical difference in the numbers of the commutator segments to which an element is connected is called the commutator pitch and is represented by the letter Y. Thus in Fig. 72 the terminals of the elements are connected to adjacent segments and hence the commutator pitch is 1; while in Figs. 82 and 84, the commutator pitches are 2 and 3 respectively. In Fig. 73 the terminals of an element are under different brushes and the commutator pitch is equal to 7.

Slot Pitch. In the case of slotted armature cores, the difference in the numbers of the slots, assuming the slots are numbered consecutively, in which the two sides of an element are placed is called the slot pitch of the winding or the throw of the coil in terms of slots.

Progressive and Retrogressive Windings. Right-handed windings are called progressive windings and left-handed windings are called retrogressive windings. A lap winding is right-handed if Y_1 is greater than Y_2, and left-handed if Y_2 is greater than Y_1. In other words, if you face the commutator end of an armature,

the winding is right-handed if you advance around the commutator in a clockwise direction as you trace through the elements in a clockwise direction. The winding shown in Fig. 72 is right-handed. In the case of a wave winding, it is right- or left-handed according to whether you arrive at a segment to the right or left of the one from which you started after having traced through $p \div 2$ elements of the winding in a clockwise direction. The winding shown in Fig. 73 is right-handed.

Resultant Advance or Retreat of a Winding. The algebraic sum of the front and back pitches of a winding is a measure of the resultant advance or retreat per element in tracing through the

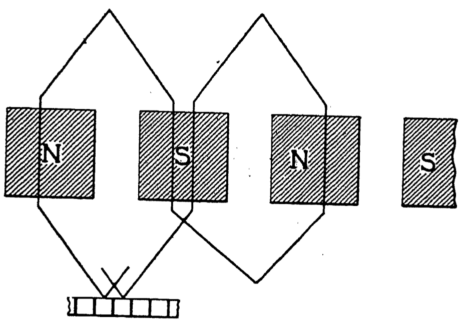

Fig. 85. Element Having Four Active Sides

winding, and it is usually expressed in terms of the commutator pitch Y. In the case of a lap winding,

$$Y_1 + (-Y_2) = 2Y \tag{1}$$

and in a wave winding

$$Y_1 + Y_2 = 2Y \tag{2}$$

In the above equations the factor 2 is introduced because each element is supposed to have two sides. In certain cases there are more than two sides to an element, as shown in Figs. 85 and 86, and in such cases the algebraic sum of the front and back pitches for each element will have to be taken.

Field Displacement. By field displacement is meant the amount that the two segments which form the terminals of an

element lack in occupying exactly the same position with respect to the polar axes. Field displacement is measured in commutator segments and represented by the letter m. In all lap windings $m = Y$, thus in Fig. 72, $m = Y = 1$, and again, in Fig. 81, $m = Y = 2$. In wave windings, such as the one shown in Fig. 73, the terminals of an element are separated by a space approximately equal to a double-pole pitch. The double-pole pitch—that is, the distance between corresponding positions on adjacent poles of like polarity, or points around the field structure that are 360 electrical degrees apart—may be expressed in terms of commutator segments by dividing the total number of segments S by the pairs of poles. Thus

$$\text{double-pole pitch} = S \div \frac{p}{2} = \frac{2S}{p}$$

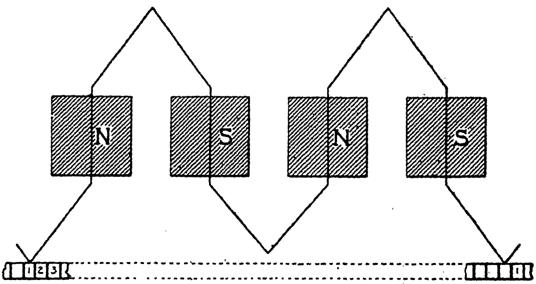

Fig. 86. Element Having Four Active Sides

The distance between the terminals of an element measured in commutator segments is equal to the commutator pitch Y, so that

$$\frac{2S}{p} \neq Y = m \tag{3}$$

or

$$Y = \frac{2S}{p} \pm m \tag{4}$$

The sign of m determines whether the winding is right- or left-handed. If m is positive, the commutator pitch is greater than the double-pole pitch and the winding is right-handed, while if m is negative the commutator pitch is less than the double-pole pitch and the winding is left-handed.

In lap and ring windings, m is always a whole number, while in wave windings m may be a fraction. Thus in Fig. 73 m is equal to $\frac{1}{2}$.

Relation Between Number of Paths, or Circuits, and Winding and Commutator Pitches. One complete circuit will have been traced through in any winding when the sum of the field displacements of the elements traced through from any arbitrarily chosen commutator segment is equal to a pole pitch measured in commutator segments. In the process of tracing through one of the circuits a certain number of commutator segments, S' (not necessarily an integral number) will be encountered, to each of which there corresponds a field displacement m, and the total displacement is mS'.

$$mS'=\frac{S}{p} \tag{5}$$

or

$$\frac{S}{S'}=mp \tag{6}$$

Since there are S' segments encountered per circuit through the winding, the total number of circuits a must be

$$a=\frac{S}{S'} \tag{7}$$

which must be a whole number, therefore

since $$\frac{S}{S'}=mp$$

$$a=mp \tag{8}$$

or

$$m=\frac{a}{p} \tag{9}$$

General Relations. In the case of a lap winding, equation (1) may be rewritten so as to obtain the value of the commutator pitch Y, which is equal to $\pm m$ and also $\pm\frac{a}{p}$ from equation (9).

Thus $$Y=\frac{Y_1+(-Y_2)}{2}=\pm m=\pm\frac{a}{p} \tag{10}$$

In the case of a wave winding, the value of Y may be determined

by rewriting equation (2), which is equal to the value of Y as given in equation (4).

Thus
$$Y=\frac{Y_1+Y_2}{2}=\frac{2S}{p}\pm m \tag{11}$$

Since $m=\frac{a}{p}$ from equation (9), then equation (10) may be rewritten as follows:

$$Y=\frac{2S\pm a}{p} \tag{12}$$

The only difference in the two expressions for the value of Y as given in equations (10) and (12) is $\frac{2S}{p}$ which corresponds to a double-pole pitch and expresses the fact that the terminals of an element having two sides are separated by that amount. In the case of a winding similar to the one shown in Fig. 86, the term $\frac{2S}{p}$ would be replaced by $\frac{4S}{p}$. In general the coefficient of $\frac{S}{p}$ represents what is called the field step (f), and it is numerically equal to the number of single-pole pitches included between the terminals of an element. In general, therefore,

$$Y=\frac{fS\pm a}{p} \tag{13}$$

In the case of the lap winding, the terminals of an element occupy positions in the same field zone, so that $f=o$, and in the case of a wave winding f is usually 2.

Numbering the Sides of an Element. In the case of a drum winding, the number of half-elements must be even; and if these half-elements are numbered consecutively, one-half of them will bear even numbers and the remaining half will bear odd numbers. In leaving a commutator segment and passing to the back end of the armature there must be a return path from the back end of the armature to the front end; and the numbering of the sides of the elements may be so arranged that the even numbers will constitute the sides of the elements leading to the back end of the armature and the odd numbers will comprise all the sides of the elements leading to the front of the armature. This will result in

even-numbered sides being connected to odd-numbered sides at both ends of the armature, and, therefore, the front and back pitches must be odd. The method of carrying out this system of numbering is shown in Fig. 87.

Application of General Equation to Lap or Parallel Windings. In the case of a lap winding there are no restrictions upon the number of elements, which may be even or odd. Practically all commercial windings have only two sides to an element, so that

$$Y_1+(-Y_2)=2Y=\pm\frac{2a}{p}=\pm 2m \qquad (14)$$

From the above equation, it is readily seen that the front and back

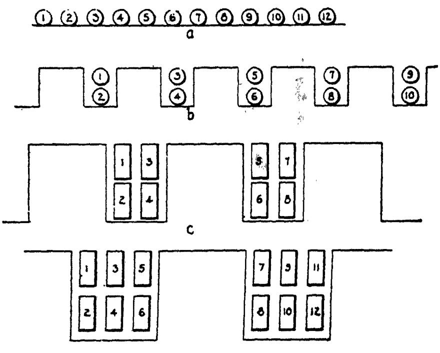

Fig. 87. Methods of Numbering the Sides of an Element

pitches must differ by twice the multiplicity of the winding and, in addition, they must be odd, as already explained.

The values of Y_1 and Y_2 should not differ too much from the value of the pole pitch $\frac{2S}{p}$, as otherwise the electromotive forces induced in the two sides of the elements will not act together around the element as effectively as they should. In certain types of windings, called chord or fractional-pitch windings, the value of the front and back pitches are purposely made larger or smaller than the pole pitch.

The application of these rules may be observed by an inspection of Fig. 72, in which $Z=24$, $S=12$, $p=4$, and $a=4$; then

$$Y=m=\frac{a}{p}=1 \quad Y_1+(-Y_2)=2\,Y=2 \quad Y_1=7 \quad Y_2=-5.$$

If the values of the back and front winding pitches had been made 9 and -7 or 5 and -3 respectively the winding would still close, but it would be a rather exaggerated form of chord winding.

Since the field displacement in a lap or parallel winding is numerically equal to the multiplicity of the winding, and since $m=\frac{a}{p}=Y$, it follows that in an m-plex lap winding the commutator pitch equals the degree of multiplicity. For example, in a simplex lap winding the terminals of an element are connected to adjacent segments; in a duplex winding the terminals of an element are separated by one segment; in a triplex lap winding the terminals of an element are separated by two segments, etc.

Application of General Equation to Wave or Series Winding. The general equation

$$Y=\frac{fS\pm a}{p} \tag{15}$$

reduces to $Y=\frac{Y_1+Y_2}{2}=\frac{2S\pm a}{p}$ for the majority of commercial wave windings.

It is obvious from an inspection of this last equation that the selection of the number of commutator segments S, and therefore the number of active inductors, is not nearly as unlimited as in the case of the lap windings. A simplex wave winding for a four-pole machine is shown in Fig. 73, in which $p=4$, $a=2$, $f=2$, and $2S=26$; hence,

$$Y=\frac{26\pm 2}{4}=7 \text{ or } 6$$

The value of Y_1 and Y_2 should be approximately equal to $\frac{2S}{p}=\frac{26}{4}=6\frac{1}{2}$. It is impossible to have a fractional pitch, and since the pitches must be odd we will select $Y_1=Y_2=7$. A pitch 7 for Y_1 and 5 for Y_2 would do, or $Y_1=5$ and $Y_2=7$ would do.

Use of Dummy Coils In complying with the requirements of equation (**15**), use must be made quite often of what are called dummy elements, or coils. For example, suppose you want to place a simplex wave winding on an armature core having 63 slots and you want to place four half-elements in each of the slots. This means that the total number of half-elements is equal to 4×63, or 252. Substituting in the general equation for Y:

$$Y = \frac{2 \times 126 \pm 2}{4} = 63\tfrac{1}{2} \text{ or } 62\tfrac{1}{2}$$

Neither of these values of Y is possible, since the value must be an integer. The nearest values of $2S$ that will make Y an integer are 250 or 254. The value of $2S = 254$ is impossible, since the maximum number of half-elements that can be placed on the armature core is 252. Taking $2S = 250$, it follows that there are two half-elements that are not a part of the winding, and these

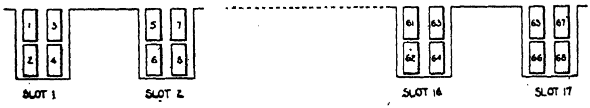

Fig. 88. Location of Half-Elements in Slots

two half-elements are merely put in two of the slots in which there are only three active half-elements to fill up the space and help keep the armature in mechanical balance. Therefore,

$$Y = \frac{250 \pm 2}{4} = 63 \text{ or } 62$$

Since Y_1 and Y_2 must be odd, and since the average pitch Y must be approximately equal to $2S \div p$, then the following pitch values are possible:

$$\begin{cases} Y_1=63 \\ Y_2=63 \end{cases} \begin{cases} Y_1=61 \\ Y_2=65 \end{cases} \begin{cases} Y_1=65 \\ Y_2=61 \end{cases} \begin{cases} Y_1=63 \\ Y_2=61 \end{cases} \begin{cases} Y_1=61 \\ Y_2=63 \end{cases} \begin{cases} Y_1=63 \\ Y_2=65 \end{cases} \begin{cases} Y_1=65 \\ Y_2=63 \end{cases}$$

Location of Half-Elements in Slots. Many other combinations in addition to the above may be used. Now before selecting the pitches, let us investigate the location of the different half-elements in the slots as shown in section in Fig. 88. The half-elements *1* and *3* in the top of slot *1* should be connected to two

half-elements in the bottom of the same slot, such as half-elements *62* and *64*, respectively, in slot *16*, or half-elements *66* and *68*, respectively, in slot *17*. In connecting to half-elements *62* and *64* a back pitch of *61* will be required, and in connecting to half-elements *66* and *68* a back pitch of *65* will be required. Connecting the half-elements in this manner will permit two of the elements being taped and insulated complete as a unit and then installed on the armature core. If a back pitch of *61* is used, the front pitch should be *65;* and if a back pitch of *65* is used, the front pitch should be *61*.

Field Displacement. The field displacement in a wave winding is equal to $\frac{a}{p}$, so that after tracing through $\frac{p}{2}$ elements, which corresponds to going around the surface of the armature core once, the total displacement is

$$\frac{p}{2}\times\frac{a}{p}=\frac{a}{2} \text{ commutator segments}$$

Hence for a simplex wave winding, $a=2$, the end of the $\frac{p}{2}$ element from the starting point connects to a segment adjacent to the starting segment. The final segment may be to the right or left of the starting segment according to whether the winding is right- or left-handed. In tracing through a duplex wave winding you terminate at a segment two removed from the starting segment, to the right or left, after passing through $\frac{p}{2}$ elements of the winding.

Pitch Values. Wave windings are frequently wound so that there are more than two circuits between brushes. For example, the armature core having 63 slots and 4 half-elements per slot may be wound with a four-circuit wave winding. Substituting in the general equation for Y

$$Y=\frac{252\pm4}{4}=64 \text{ or } 62$$

Since Y_1 and Y_2 must be odd, the following combinations may be used:

$$\begin{cases} Y_1=65 \\ Y_2=63 \end{cases} \quad \begin{cases} Y_1=63 \\ Y_2=65 \end{cases} \quad \begin{cases} Y_1=61 \\ Y_2=63 \end{cases} \quad \begin{cases} Y_1=63 \\ Y_2=61 \end{cases}$$

Other combinations for Y_1 and Y_2 may of course be used, and the selection of the pitches will depend upon the arrangement of the inductors in the slots, as explained above.

Method of Determining the Re-entrancy of a Winding. If both sides of the general equation

$$Y = \frac{fS \pm a}{p}$$

are divisible by a number q, we have

$$\frac{Y}{q} = \frac{\frac{fS}{q} \pm \frac{a}{q}}{p} \tag{16}$$

or

$$Y' = \frac{fS' \pm a'}{p} \tag{17}$$

This last equation means that the original winding is in reality made up of q independent windings, and that there are S' elements in each of these windings. The commutator pitch of any one of these independent windings is equal to Y' when it is counted with respect to the S' segments connected to each of the independent windings.

In general the winding will be multiplex and multiply re-entrant of the qth degree, provided the average of the front and back pitches Y and the total number of commutator segments S have a common factor q. If the values of Y and S are prime to each other, that is, they have no common factor, then the winding is singly re-entrant. Thus in a duplex lap winding Y is equal to 2; and if the value of S is divisible by 2, the winding is doubly re-entrant, otherwise it is singly re-entrant. In a triplex lap winding Y is equal to 3; and if the value of S is divisible by 3, the winding is trebly re-entrant, otherwise it is singly re-entrant. In a quadruplex lap winding Y is equal to 4; and if the value of S is divisible by 4, the re-entrancy of the winding is 4. If the values of Y and S for a quadruplex winding are not divisible by 4 but are both divisible by 2; then the winding is doubly re-entrant. If the values of Y and S are not divisible by 2 or 4, then the winding is singly re-entrant.

Duplex Windings. In all ordinary duplex wave windings the value of the field displacement f is 2, and

$$Y=\frac{2S\pm4}{p}=\frac{2(S\pm2)}{p}$$

In the above equation if Y is an even number, that is, if it is divisible by 2, the value of S must also be even because $\frac{S\pm2}{p}$ must be a whole number and p is always an even number. Hence a duplex wave winding is doubly re-entrant if Y is even, and singly re-entrant if Y is odd.

Triplex Windings. In all ordinary triplex wave windings the value of the field displacement f is 2 and

$$Y=\frac{2S\pm6}{p}=\frac{2(S\pm3)}{p} \qquad (18)$$

Let us assume that Y is divisible by 3 and it contains 3 x times, then $Y=3x$. Substituting this value of Y in equation (18) gives

$$3x=\frac{2(S\pm3)}{p}$$

Multiplying by p and dividing by 2 gives

$$3x\frac{p}{2}=S\pm3$$

Dividing by 3 gives

$$x\frac{p}{2}=\frac{S}{3}\pm1 \qquad (19)$$

Since the value of the left-hand side of the above equation is a whole number, then the right-hand side must be a whole number, or S must be divisible by 3, and the winding will be trebly re-entrant. Hence a triplex wave winding is trebly re-entrant when the value of Y is divisible by 3, and the winding will be singly re-entrant if Y is not divisible by 3.

Quadruplex Windings. In the quadruplex wave windings the re-entrancy may be one, two, or four, according to the following relations: If Y is divisible by four, the winding is quadruply re-entrant; if the value of Y is divisible by 2 but not by 4, the winding is doubly re-entrant. If the value of Y is not divisible by 2 or 4, the winding is singly re-entrant.

The best way to obtain a clear understanding of the application of the general equations and relations is to study a number of different windings and apply the equations and relations to each of them. This will be done for lap and wave windings in the following sections.

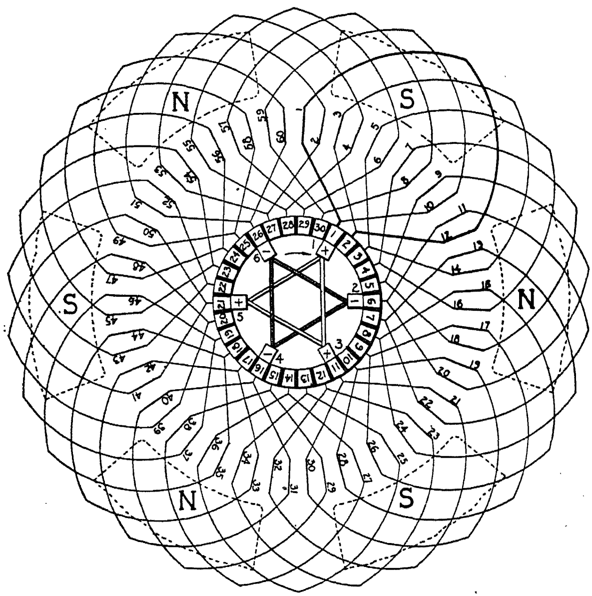

Fig. 89. Simplex, Singly Re-entrant, Progressive Lap Winding for a Six-Pole Machine
N = 60 S = 30 $Y_1 = +11$ $Y_2 = -9$
$Y = +1$ a = 6 f = 0

Examples of Lap Windings. A six-pole, drum, simplex, singly re-entrant, progressive lap winding is shown in Fig. 89, and a development of the winding is given in Fig. 90. This winding is of the lap type because the front and back pitches lead you around the armature in different directions as you trace through the winding. Inductor *1* is connected to inductor *12* at the back end of the armature, so that $Y_1 = +11$, and inductor *12* is connected to induc-

tor *3* at the front or commutator end, so the value of the front pitch Y_2 is -9.

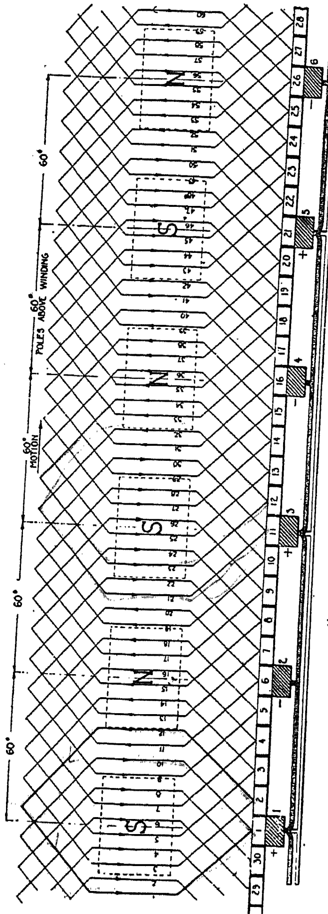

Fig. 90. Development of Winding Shown in Fig. 89

The winding is singly re-entrant because the terminals of an element are connected to adjacent segments, or $Y=+1$. The

winding is progressive because Y_1 is greater than Y_2, or you advance around the armature in a clockwise direction as you trace through the elements in a clockwise direction. It will be found that there are six circuits through the winding, and six brush sets will be required, unless the winding or commutator is cross-connected.

A six-pole, drum, duplex, singly re-entrant, progressive lap winding is shown in Fig. 91, and a development of the winding is given in Fig. 92. This winding could be changed to a retrogressive type by interchanging the values of the front and back winding pitches. In changing from the progressive to the retrogressive type, the connections of the ends of the elements are crossed and the polarity of the armature as a generator and its direction of rotation as a motor, all other things remaining unchanged, will be reversed. The winding is duplex because $Y=2$ and it is singly re-entrant because S is not divisible by 2. The front and the back winding pitches differ by two times the multiplicity, or 4.

A six-pole, drum, duplex, doubly re-entrant, progressive lap winding is shown in Fig. 93, and a development of the winding is given in Fig. 94. Checking by our rule it will be seen that the winding is duplex because $Y=2$ and it is doubly re-entrant because S is divisible by 2. It may be changed to a retrogressive type by interchanging the values of the front and the back winding pitches.

A six-pole, drum, triplex, singly re-entrant, progressive lap winding is shown in Fig. 95, and a development of the winding is given in Fig. 96. The winding is triplex because $Y=3$. The value of S is not divisible by 3 and consequently the winding is singly re-entrant.

A six-pole, drum, triplex, trebly re-entrant, progressive lap winding is shown in Fig. 97, and a development of the winding is given in Fig. 98. Again checking by the rule we find that in this case the value of S is divisible by 3, hence the winding is trebly re-entrant.

Examples of Wave Windings. A six-pole, drum, simplex, singly re-entrant, progressive wave winding is shown in Fig. 99, and a development of the winding is given in Fig. 100. The

winding is simplex, because, in starting with any commutator segment and after tracing through $\frac{p}{2}$ elements, you arrive at a segment adjacent to the one from which you started. The segment you end on, after tracing through $\frac{p}{2}$ elements in a clockwise

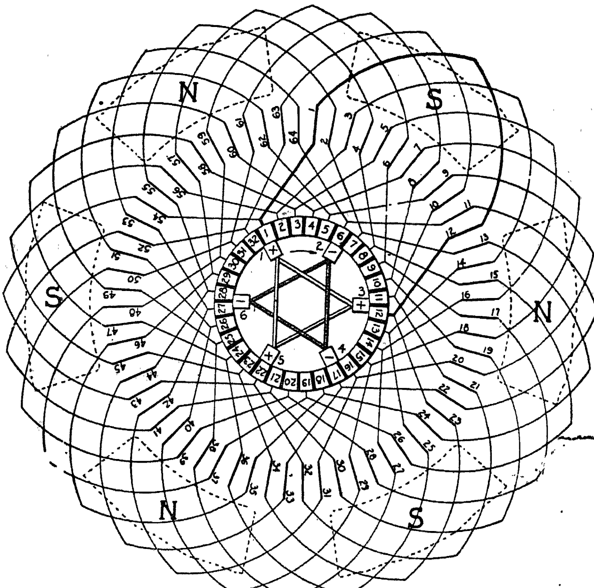

Fig. 99. Simplex, Singly Re-entrant, Progressive Wave-Winding for a Six-Pole Machine
$N = 64$ $S = 32$ $Y_1 = +11$ $Y_2 = +11$
$Y = +11$ $a = 2$ $f = 2$

direction, in this case, is to the right of the one from which you started, hence the winding is progressive. Had you ended on a segment to the left of the one from which you started, after tracing through $\frac{p}{2}$ elements, the winding would have been retrogressive. The winding is singly re-entrant as there is only one closure and the multiplicity cannot in any case exceed the degree

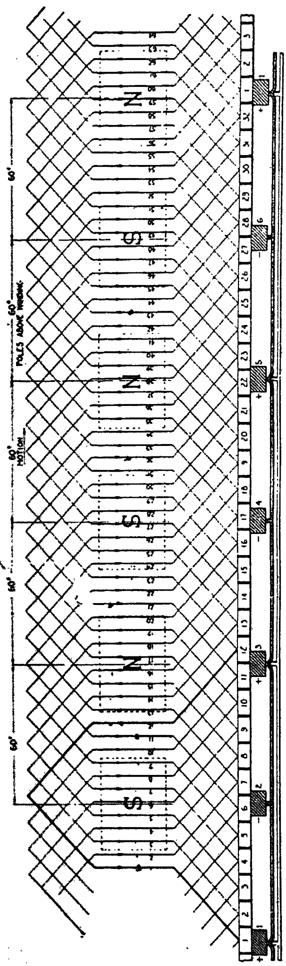

Fig. 100. Developed Diagram of Winding Shown in Fig. 99

of re-entrancy. There are two circuits through the winding, as is always the case in a simplex wave winding. The value of the field step f is 2, since the terminals of an element are separated by approximately two single-pole pitches.

A six-pole, drum, duplex, singly re-entrant, progressive wave winding is shown in Fig. 101, and a development of the winding is given in Fig. 102 The winding is duplex because in starting with any commutator segment and tracing through $\frac{p}{2}$ elements you arrive at a segment two removed from the one from which you started. The terminating segment after tracing through $\frac{p}{2}$ elements is to the right of the one from which you started, hence the winding is progressive. The winding is singly re-entrant because Y and S are not divisible by 2 The number of circuits through the winding is twice the multiplicity, or 4. The value of the field displacement f is 2.

A six-pole, drum, duplex, doubly re-entrant, retrogressive wave winding is shown in Fig. 103, and a development of the winding is given in Fig. 104. The winding is doubly

re-entrant because after tracing through $\frac{p}{2}$ elements in a clockwise direction you arrive at a segment two removed from the one from which you started. It is retrogressive because you terminate at a segment to the left of the one from which you started. The winding is doubly re-entrant because the values of Y and S are divisible by 2. There are four circuits through the winding. The front and back pitches are both odd, but differ by 2. The values of the pitches may be interchanged without changing the type of the winding, as in the case of the lap winding, which changes from a progressive to a retrogressive, or from a retrogressive to a progressive, when the values of the front and back pitches are interchanged, as explained in the preceding section.

A six-pole, drum, triplex, singly re-entrant, retrogressive wave winding is shown in Fig. 105, and a development of the winding is given in Fig. 106. The winding is triplex because after tracing through $\frac{p}{2}$ elements you arrive at a segment three removed from the one from which you started, and it is retrogressive because you terminate at a segment to the left of the one from which you started. It is singly re-entrant because the values of Y and S are not divisible by 3. The number of circuits through the winding is equal to twice the multiplicity, or 6.

A six-pole, drum, triplex, trebly re-entrant, progressive, wave winding is shown in Fig. 107, and a development of the winding is given in Fig. 108. This winding is trebly re-entrant because the values of Y and S are both divisible by 3.

Reduction of Total Inductors to Elements of a Single Turn. In each of the windings shown in Figs. 89 to 108 inclusive, each element is represented as being composed of only two inductors. This is not always the case. So in applying the general equations, it is necessary first to reduce the total number of inductors to the number that would exist on the armature if each element were composed of only two inductors, by dividing the total number of inductors in the winding by the number of turns in one of the elements. For example, if a six-pole, simplex, singly re-entrant lap winding is composed of 120 inductors and there are only 30 commutator segments, then each element is composed of 4

TABLE II

Winding Table for Six-Pole, Duplex, Singly Re-entrant Progressive Lap Winding, Shown in Fig. 91

Y_2	Y_1	Y_2	Y_1	Y_2	Y_1	Y_2
B	F	B	F	B	F	
1	22	5	26	9	30	
13	34	17	38	21	42	
25	46	29	50	33	54	
37	58	41	62	45	66	
49	70	53	74	57	78	
61	82	65	86	69	90	
73	94	77	98	81	102	
85	106	89	110	93	114	
97	118	101	4	105	8	
109	12	113	16	117	20	
3	24	7	28	11	32	
15	36	19	40	23	44	
27	48	31	52	35	56	
39	60	43	64	47	68	
51	72	55	76	59	80	
63	84	67	88	71	92	
75	96	79	100	83	104	
87	108	91	112	95	116	
99	2	103	6	107	10	
111	14	115	18	1	...	

inductors, or two turns. In this case the number of inductors must be divided by 2 in order to get the value of the number of half-elements.

Winding Tables for Armature Windings. All the electrical connections in an armature winding may be readily indicated by means of a winding table as shown on pages 84, 85, and 86. Thus in

TABLE III

Winding Table for Six-Pole, Duplex, Doubly Re-entrant Retrogressive Wave Winding, Shown in Fig. 103

Y_2	Y_1	Y_2	Y_1	Y_2	Y_1	Y_2

B	F	B	F	B	F
1	22	41	62	87	102
121	18	37	58	77	98
117	14	33	54	73	94
113	10	29	50	69	90
109	6	25	46	65	86
105	2	21	42	61	82
101	122	17	38	57	78
97	118	13	34	53	74
93	114	9	30	49	70
89	110	5	26	45	66
85	106	1	...	...	...
...	...	3	24	43	64
83	104	123	20	39	60
77	100	119	16	35	56
73	96	115	12	31	52
69	92	111	8	27	48
65	88	107	4	23	44
61	84	103	124	19	40
57	80	99	120	15	36
53	76	95	116	11	32
49	72	91	112	7	28
45	68	87	108	3	...

Table II, which corresponds to the winding shown in Fig. 91, we find the following connections. Starting with inductor *1* you pass to the back of the armature, which is indicated in the table by

TABLE IV

Winding Table for Six-Pole. Triplex, Trebly Re-entrant Progressive Wave Winding, Shown in Fig. 107

Y_2	Y_1	Y_2	Y_1	Y_2	Y_1	Y_2

B	F	B	F	B	F
1	22	7	28	13	34
19	40	25	46	31	52
37	58	43	64	49	70
55	76	61	82	67	88
73	94	79	100	85	106
91	112	97	118	103	4
109	10	115	16	1	...
...	...	...	...	3	24
9	30	15	36	21	42
27	48	33	54	39	60
45	66	51	72	57	78
63	84	69	90	75	96
81	102	87	108	93	114
199	120	105	6	111	12
117	18	3	...	...	...
...	....	5	26	11	32
17	38	23	44	29	50
35	56	41	62	47	68
53	74	59	80	65	86
71	92	77	98	83	104
89	110	95	116	101	2
107	8	113	24	119	20
5	...	....			

the letter B, at the head of the column; then you advance by an amount equal to the back pitch Y_1, to inductor *22* and then to

the front end of the armature. From the front end of inductor *22* you drop back by an amount equal to Y_2 to inductor *5*, etc. All the inductors composing the winding in Fig. 91 are passed through before you return to the starting point.

The winding shown in Fig. 103 closes twice, see Table III.

The winding shown in Fig. 107 closes three times, see Table IV.

Time of Commutation for Lap and Wave Windings. The time of commutation of an element of an armature winding is equal to the time in seconds that the element is short-circuited by the brushes, the latter forming an electrical connection between the segments of the commutator to which the element is connected.

Simplex Lap Winding. In the case of a simplex lap winding the terminals of an element are connected to adjacent commutator segments as shown diagrammatically in Fig. 109. The two segments *1* and *2* both will be in contact with the brush while the surface of the commutator is moving a distance equal to the width of the brush minus the thickness of the insulation between the segments. The time of commutation is given by the following equation:

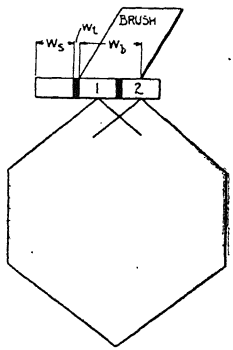

Fig. 109. Element of Simplex Lap Winding Short-Circuited by Brush

$$t_c = \frac{W_b - W_i}{V_c}, \qquad (20)$$

in which t_c is time of commutation in seconds; W_b is width of brush in inches; W_i is width of insulation in inches; and V_c is velocity of the commutator surface in inches per second.

Duplex Lap Winding. In the case of a duplex lap winding the terminals of an element are connected to segments which are not adjacent but are separated by one intervening segment, as shown diagrammatically in Fig. 110. Segments *1* and *3* are both in contact with the brush while the commutator is traveling a distance equal to the width of the brush minus the width of a segment plus twice the thickness of the insulation between the segments. The time of commutation will be given by the following equation:

$$t_c = \frac{W_b - (W_s + 2W_i)}{V_c} \tag{21}$$

in which W_s stands for the width of a segment and the remaining symbols have the same meaning as given above.

Triplex Lap Winding. The time of commutation for a triplex lap winding is given by the following equation:

$$t_c = \frac{W_b - (2\,W_s + 3\,W_i)}{V_c} \tag{22}$$

Wave Windings. In the case of a wave winding the terminals of an element are connected to commutator segments which are approximately 360 electrical degrees apart. The amount by which the distance between the terminals of an element, in the case of a wave winding, differs from 360 electrical degrees, measured in commutator segments, is called the field displacement. Field displacement is represented by the letter m, and its numerical value for the different kinds of wave windings may be determined as follows: In a simplex wave winding m is equal to 1 divided by the number of pairs of poles; in a duplex wave winding m is equal to 2 divided by the number of pairs of poles, etc. In general m is equal to the multiplicity of the winding divided by the pair of poles. The value of m is in reality measured in a unit which represents the width of one segment plus the thickness of the insulation between segments. In general the time of commutation for a wave winding is given by the following equation:

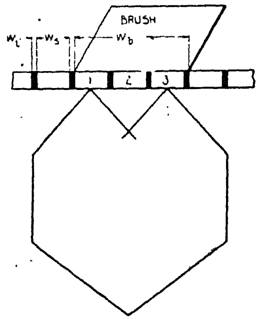

Fig. 110. Element of Duplex Lap Winding Short-Circuited by Brush

$$t_c = \frac{W_b - m(W_s + W_1) + W_s}{V_c} \tag{23}$$

The above equation assumes there are as many brushes as there are poles. If some of the brushes have been removed, the m in the above equation must be multiplied by the number of double-pole pitches in the particular region from which the brushes

have been removed. An element of a wave winding is shown in Fig. 111 and it is short-circuited by two brushes and the outside connection between the brushes.

Equipotential Connections. It sometimes happens that the e.m.f.'s induced in the different paths of an armature winding are not all equal and these unequal e.m.f.'s, due to the low resistance of the armature, may give rise to large internal equalizing currents, and excessive heating of the winding and sparking at the brushes may result unless some preventive measures are employed. The

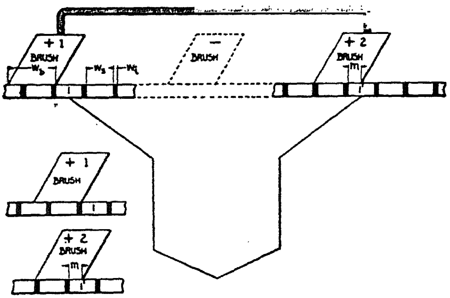

Fig. 111. Element of a Wave Winding Short-Circuited by Two Brushes and Outside Connection

following are some of the causes of unequal e.m.f.'s in the different paths:

1. The armature may not be exactly centered with respect to the pole shoes owing to irregularities in construction or wear of the bearings. The above condition results in lack of uniformity in the air gap, causing some of the poles to carry more magnetic flux than others; thus the inductors under their influence have a greater e.m.f. induced in them than i induced in the inductors under the weaker poles. The effect of unequal e.m.f.'s is most noticeable in lap and ring armatures, as all of the inductors in any one path are under one particular pole. In a wave winding the inductors in the different circuits are distributed under the different poles, and all circuits are affected alike.

2. The poles may not be identical in construction, even though the air gaps are uniform. Thus the joints between the cores and the yoke, or between the shoes and the cores, may not all be equally good, or the magnetizing effect of the field coils may differ owing to a difference in turns or current, as when the coils are connected in parallel.

3. The armature circuits may be unsymmetrical because the number of inductors is not a multiple of the number of paths.

The equalizing currents are a source of loss; to minimize them the greatest possible degree of magnetic and electrical symmetry should be secured. To overcome the remaining difficulties, such as sparking at the brushes, use is made of equipotential connections (low-resistance conductors joining points in the winding), which, under ideal conditions, would at all times have the same potential. When an unbalance occurs, currents will

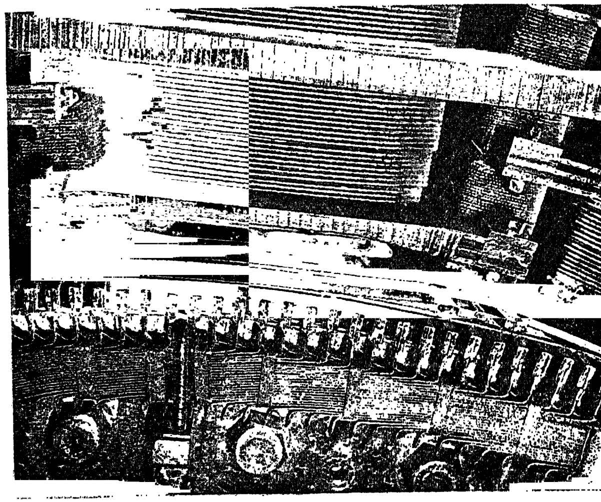

Fig. 112. Equalizer Connections on a Large Generator
Courtesy of the General Electric Company

flow through these connections, relieving the brushes of the extra current and thus reducing sparking. The equalizer connections on a large generator are shown in Fig. 112. These connections are usually made at the back end of the armature.

MOUNTING ARMATURE WINDINGS

The different methods of armature winding have already been treated theoretically; it now remains to consider the mechanical arrangements or means employed to carry out the scheme of winding adopted.

Drum Windings. Drum windings may be subdivided into hand windings, evolute windings, barrel windings, bastard drum windings, and form windings, according to the manner in which the end-connections are made. It is essential that these latter be good conductors, well insulated from each other to facilitate repairs and ventilation, and mechanically sound.

Hand Windings. Hand windings, historically the first, are now seldom used, except for special machines. They involve a clumsy overlapping of wires at the ends of the armature, and this stops ventilation and hinders repairs; moreover, the outer layers, overlying those first wound, bring into close proximity inductors of widely different voltages.

Evolute Windings. Evolute windings, so named from the method of uniting the conductors by means of spiral end-connectors, were quite early devised to overcome the objections to the hand windings. In Fig. 113, which illustrates this construction, each inductor in the form of a bar is connected to the next by means of two evolute spiral copper strips, one bending inwardly, the other outwardly, their junction being in some cases secured to a block of wood upon the shaft. Their outer ends are attached to the bars by rivets or silver solder.

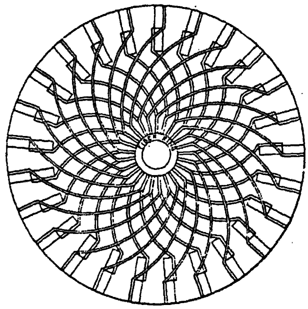

Fig. 113. Evolute Armature Winding

A common form of such end-connector is shown in Fig. 114, another form is made of copper strip, folded. In place of the wooden block referred to above, the middle part of the evolute connector may be anchored to an insulated clamping device built up like a commutator and called from this resemblance a false commutator.

In evolute windings the spiral connectors lie in two planes, back of one another; hence it is necessary that the armature bars should project to different distances beyond the core body, the shorter ones being joined to the inner layer of evolutes, the longer

ones to the outer layer. For this purpose it is convenient to arrange one short and one long bar in a slot, side by side, as in Fig. 115, or in the finished armature of Fig. 116.

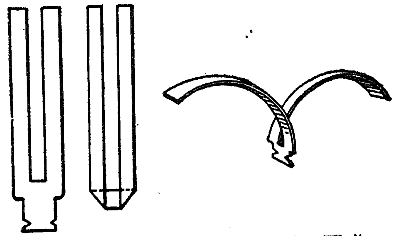

Fig. 114. Spiral End Connectors for Evolute Winding

Barrel Windings. Barrel windings were devised by C. E. L. Brown in 1892, as an improvement upon the evolute windings just described, and are the ones most extensively used today. The method consists in arranging the inductors in two layers, so that their ends, instead of being carried down as evolutes, are continued out upon an extension of the cylindrical surface of the armature and are bent to meet obliquely in two overlapping layers. This scheme, like the evolute winding, is adapted to wave as well as to lap windings. Its only disadvantage lies in the fact that it requires the length of the armature parallel to the shaft to b greater than in the preceding case. Its great advantage lies i the excellent ventilation made possible by the larger cooling surfac

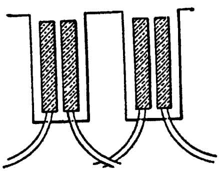

Fig. 115. Evolute Conductors in Slots

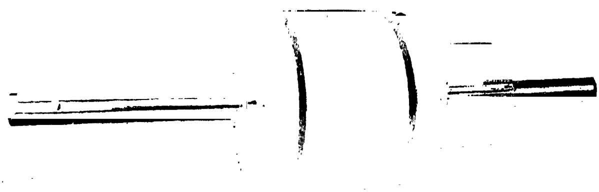

Fig. 116. Bar-Wound Armature

and the provision for air to enter the interior of the armature at the ends.

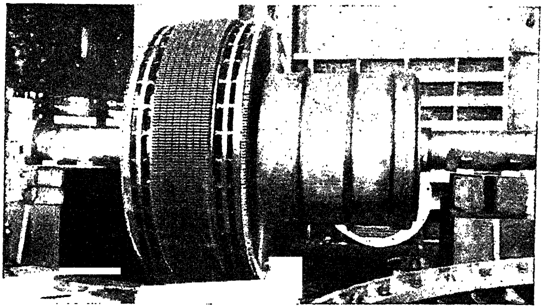

Fig. 117. Armature Core and Commutator for 3000-k.w., 300-Volt Allis-Chalmers Generator
Courtesy of Allis-Chalmers Company

A usual method of supporting the extended end-connections is to attach to the end of the armature body ventilated brackets,

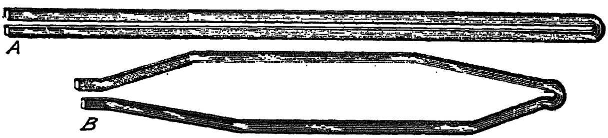

Fig. 118. Element of Lap Winding Formed from a Strip of Copper

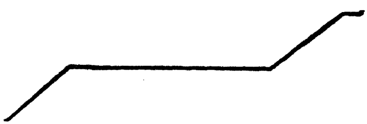

Fig. 119. Element of Wave Winding Formed from a Strip of Copper

as indicated in Fig. 117. A simple way to construct such a winding is to take a long bar of copper, and bend it as shown at *A*,

Fig. 118. The bar may be opened out as in *B*, Fig. 118, if the winding is to be lap-wound, or as in Fig. 119, if the winding is

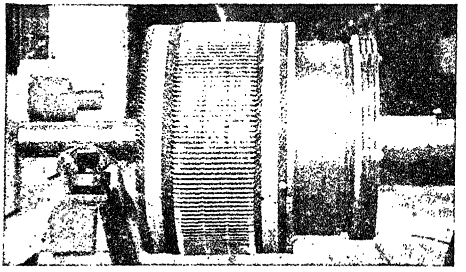

Fig. 120. Allis-Chalmers Lap-Wound Armature for 150-k.w., 240-Volt, 240-r.p.m., Three-Wire Type I Generator
Courtesy of Allis-Chalmers Company

to be wave-wound. In Figs. 120 and 121 finished armatures of this type are represented.

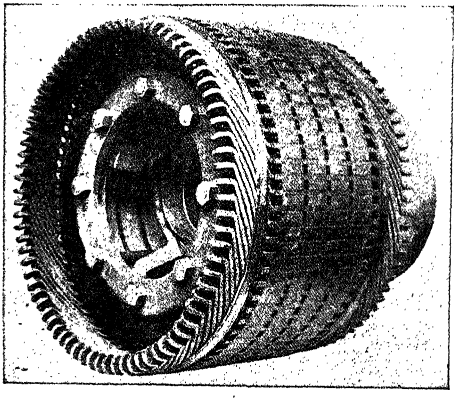

Fig. 121. General Electric Wave-Wound Armature for 125-Volt Form L.D. Generator
Courtesy of General Electric Company

Thus far the windings have been described as formed of copper bars; but it is also possible to wind either of these types with wire, shaping the coils before placing the wire in the slots.

Cases also occur where more than two layers of wire are necessary, either on account of the high voltage required, or to avoid harmful induction.

Bastard Windings. Bastard drum-windings is the name given to that class of armature windings whose end-connections, instead

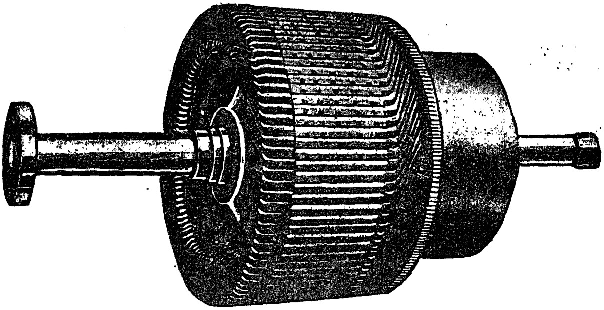

Fig. 122. Armature of Westinghouse Generator, Combination of Bastard and Barrel Winding

of being carried in toward the shaft in evolutes or elongated cylindrically, are partly inward and partly cylindrical. This has the effect of making shorter that part of the armature parallel to the shaft than is the case with the barrel winding. It requires,

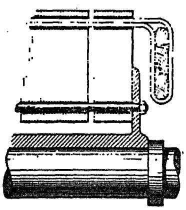

Fig. 123. Evolute Wound Armature

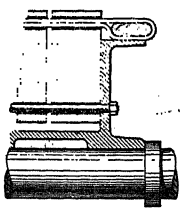

Fig. 124. Barrel-Wound Armature

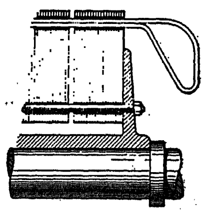

Fig. 125. Bastard-Wound Armature

however, special formers, and is applicable only to bar-wound armatures. To provide adequate ventilation, it is customary to use a barrel winding at the commutator end of the armature and a bastard winding at the other end, as shown in Fig. 122.

Fig. 118. The bar may be opened out as in *B*, Fig. 118, if the winding is to be lap-wound, or as in Fig. 119, if the winding is

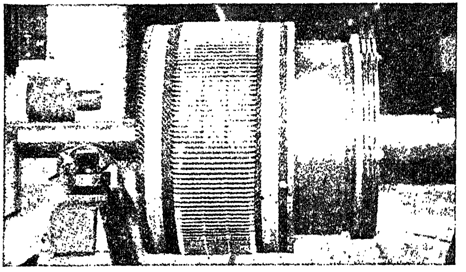

Fig. 120. Allis-Chalmers Lap-Wound Armature for 150-k.w., 240-Volt, 240-r.p.m., Three-Wire Type I Generator
Courtesy of Allis-Chalmers Company

to be wave-wound. In Figs. 120 and 121 finished armatures of this type are represented.

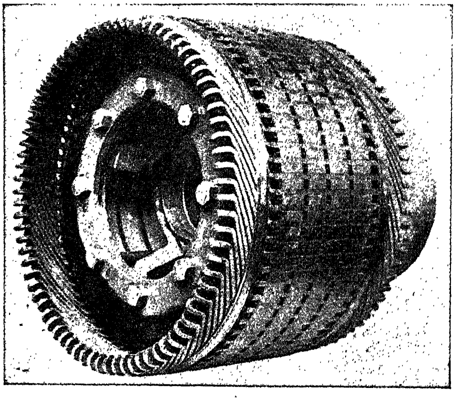

Fig. 121. General Electric Wave-Wound Armature for 125-Volt Form L.D. Generator
Courtesy of General Electric Company

Thus far the windings have been described as formed of copper bars; but it is also possible to wind either of these types with wire, shaping the coils before placing the wire in the slots.

Cases also occur where more than two layers of wire are necessary, either on account of the high voltage required, or to avoid harmful induction.

Bastard Windings. Bastard drum-windings is the name given to that class of armature windings whose end-connections, instead

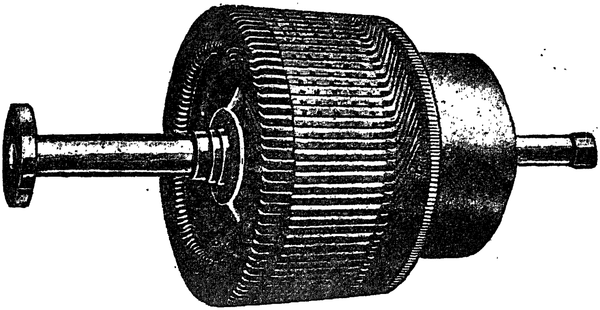

Fig. 122. Armature of Westinghouse Generator, Combination of Bastard and Barrel Winding

of being carried in toward the shaft in evolutes or elongated cylindrically, are partly inward and partly cylindrical. This has the effect of making shorter that part of the armature parallel to the shaft than is the case with the barrel winding. It requires,

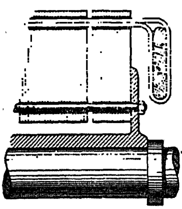

Fig. 123. Evolute Wound Armature

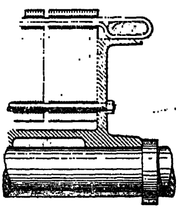

Fig. 124. Barrel-Wound Armature

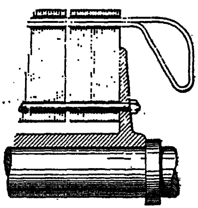

Fig. 125. Bastard-Wound Armature

however, special formers, and is applicable only to bar-wound armatures. To provide adequate ventilation, it is customary to use a barrel winding at the commutator end of the armature and a bastard winding at the other end, as shown in Fig. 122.

Figs. 123, 124, and 125 show the relation of this scheme to the two types previously mentioned.

Form-Wound Drum Windings. It was early found that hand-wound drums were both expensive in labor and unsymmetrical

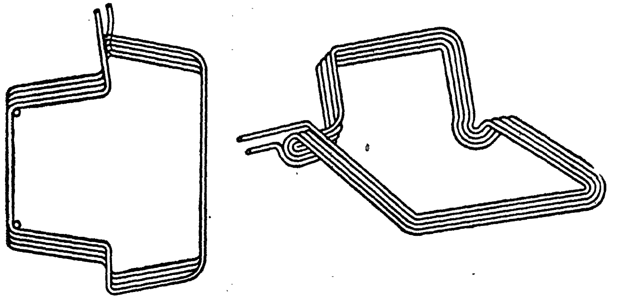

Fig. 126. Eickemeyer Form-Wound Coil, and Same Bent Up

electrically. Therefore a scheme was developed for arranging the winding in coils or formers, and then laying these formed coils in their respective places upon the core body. The individual sections of the winding are first wound and shaped upon a frame, or former (the wire being plain cotton-covered). Each section is then separately insulated by a winding of tape, usually half-lapped, and is then baked, varnished, and baked again.

Alioth, according to the patent records, was the first to devise this method. He was followed by Eickemeyer, who, in 1888,

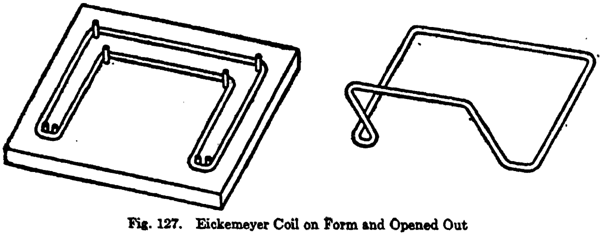

Fig. 127. Eickemeyer Coil on Form and Opened Out

patented a method of winding formed coils for evolute windings. This method attained almost universal use during the vogue of the evolute winding; and the first two stages in the construction

of such a section are illustrated in Fig. 126; Fig. 127 illustrates later type of the former, and Fig. 128 a completed armature winding built up of such coils.

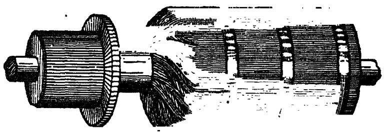

Fig. 128. Eickemeyer Armature Complete

What the Eickemeyer coil accomplishes for the evolute winding, may be accomplished for the barrel winding by use of "straight-out" formers. Fig. 129 illustrates a simple former of this type, upon which a coil for a wave winding has been wound and then opened out. Figs. 123, 124, and 125 illustrate the three principal types of formed windings, while Fig. 130 illustrates successive stages in the construction of a barrel-wound armature using formed coils.

Arrangement of Inductors in Slots. Various methods of arranging the inductors in the slots have been mentioned. The most frequent plan in large continuous-current generators is that of putting them in two layers, either two or more in a slot. Form-wound coils lend themselves to the two-layer arrangement, which, however, is adaptable for use only with parallel-sided slots. Yet by grouping the conductors six in a slot, or eight in a slot, as in Fig. 131, T-shaped teeth can be employed. It must be remembered that, owing to the magnetic shielding of the teeth, the conductors are subjected practically to centrifugal force only. Unless the pole-faces are laminated, the top breadth of the slots must be kept very narrow, i. e., not wider than $2\frac{1}{2}$ times the length of the air gap, because otherwise eddy currents would be generated in the pole-faces; also, if straight teeth are employed, they must be kept very narrow, otherwise the high flux-density required in the teeth for sparkless collection of current will not be attained.

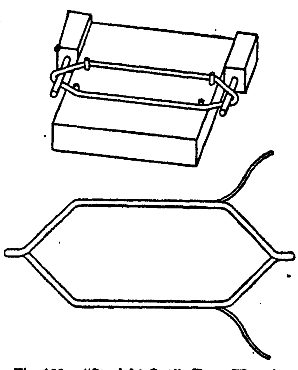

Fig. 129. "Straight-Out" Form-Wound Coil, and Coil Opened Out

All electric and magnetic considerations point to having the slots and teeth narrow and numerous; while mechanical considerations impose a limit upon the minimum width of teeth. Standard practice for parallel-wound armatures has had to choose a mean, and it is usual to put two, four, or six inductors or coil sides per slot.

Slot Insulation. The coils must be protected from injury by the walls of the slot; hence slot insulation is employed. This may consist of empire cloth 7 to 10 mils thick, with fish paper of 5 to

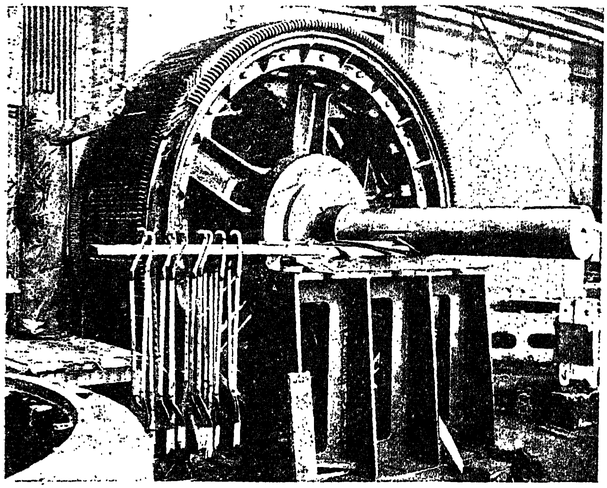

Fig. 130. Barrel-Wound Armature with Winding Partly Completed
Courtesy of Allis-Chalmers Company

7 mils either side of it. In the case of high-temperature machines, mica tubes are frequently used for slot insulation. In general, the classes of armature winding and slot insulation are defined by the American Institute of Electrical Engineers as class A, B, or C insulation, and the temperature limits of the same are as given in Table V.

Commutator and Brush Calculations. Commutators for continuous-current machines may be divided into two classes, depend-

TABLE V

Permissible Temperature and Temperature Rises for Insulation Material

Class	Description of Material	Maximum Temperature to which the Material May Be Subjected	Maximum Temperature Rise
A	Cotton, silk, paper, and similar materials, when so treated or impregnated as to increase the thermal limit, or when permanently immersed in oil; also enameled wire.[1]	105° C.	65° C.
B	Mica, asbestos and other materials capable of resisting high temperatures, in which any Class A material or binder is used for structural purposes only, and may be destroyed without impairing[2] the insulating or mechanical qualities of the insulation.	125° C.	85° C.
C	Fireproof and refractory materials, such as pure mica, porcelain, quartz, etc.	No limits specified	

[1] For cotton, silk, paper, and similar materials when neither treated, impregnated, nor mmersed in oil, the highest temperature rises shall be 10° C. below the limits fixed for Class A n Table V.

[2] The word *impairing* is here used in the sense of causing any change which would disqualify the insulation for continuous service.

ng upon whether they are for open- or closed-coil armature windngs. In the former, a special case used for arc-lighting generators, he commutator has a small number of segments separated by air aps, and each covering a considerable angle. With closedoil windings—ordinarily used or direct-current lighting and ower, in which case the terminal oltage is kept comparatively onstant, in contradistinction to eries arc-lighting machines for vhich the current is constant— he commutator is of the original

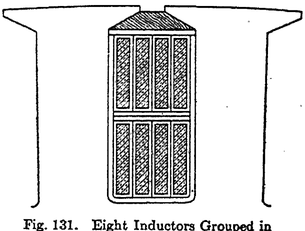

Fig. 131. Eight Inductors Grouped in a Slot

Pacinotti type, that is, it consists of a considerable number of parallel bars or segments separated by strips of insulation, usually

TABLE VI

Voltage and Number of Segments

For Machines Working at	Average Volts per Segment e_s	Average Segments per Pole or Circuit
500 to 650 volts	5 to 12	40 to 150 or more
200 to 250 volts	3 to 8	25 to 75
100 to 130 volts	2 to 4	20 to 50

mica. In both cases the completed commutator presents a cylindrical surface against which the brushes press.

Number of Segments. The number of segments depends upon the number of sections of the winding. Increasing the number of commutator segments reduces the tendency to spark at the brushes. This increase is limited, however, by the matter of cost, and by the fact that the number of sections in a drum-wound armature can never exceed one-half the number of inductors, while, in a ring-wound armature, the number of sections can never be greater than the number of inductors.

The proper number of segments is, therefore, determined by the winding of the armature, which depends upon the voltage and output of the machine. If by experience the suitable number of average volts per segment e_s of the commutator be known, then S, the number of segments, may be readily computed from the following formula

$$S = E \div e_s$$

Experience shows that the values of e_s indicated in Table VI may be chosen, although the matter is influenced by the current to be collected. If the latter be less than 100 amperes, then the value of e_s may be increased, but in no case should it exceed 15 volts.

Arnold has given the rule that the number of commutator segments must never be less than 0.037 to 0.04 times the product of the number of armature inductors into the square root of the current carried by one circuit of the armature. This rule is an empirical one based on observations with regard to sparking; nevertheless it has been found that good machines were built in which the constant was slightly less than 0.037.

The number of segments in the last consideration, is, as a matter of fact, limited by the reactance voltage or voltage of

self-inductance of the armature coils during commutation, and the turns per coil must be such that the reactance voltage in a non-interpole machine does not exceed 1.5 volts as a maximum.

Example. A 1000-kilowatt generator having 16 paths in parallel through its armature produced 500 volts at its terminals. The number of armature conductors was 2304. Hence, according to Arnold's rule, S must not be less than $0.037 \times 2304\sqrt{2000 \div 16} = 956$. As a matter of fact, 1152 segments were taken for this machine, making the number of segments equal to one-half the number of inductors.

Size of Commutator. The size of the commutator depends upon the number of segments, their thickness and the thickness of the insulation between them, and the length of the segments parallel to the shaft. The diameter is limited by the peripheral speed allowable. The length depends upon the amount of current to be collected, a density of 40 amperes per square inch being as much as should be allowed for the contact area between a carbon brush and the bar. Bars are rarely thinner than 0.2 inch or with insulation, say 0.25 inch, and the peripheral speed of the commutator seldom exceeds 3000 feet per minute; so that by keeping within these limits good results may be expected. A favorite size for commutator diameters is three-fourths that of the armature diameter.

Process of Winding a Small Armature. The complete process of winding a small armature is shown in Figs. 132 to 142 inclusive. The armature core mounted on the shaft and ready for winding is shown in Fig. 132. The support for the winding at the back end of the armature is being insulated in Fig. 133 by winding tape about it. A number of coils ready to be taped are shown in Fig. 134. The coils are being taped by hand in Fig. 135 and by means of a machine in Fig. 136. Field coils are being taped by hand in Fig. 137. After the coils are taped they are impregnated with the insulating compound by dipping them in the compound as shown in Fig. 138. The coils are then baked or allowed to dry, according to the kind of insulating compound that is used. After the coils are completed they are placed on the armature core as shown in Fig. 139. The commutator is then placed on the shaft and the lower ends of all the coils are bent to the right

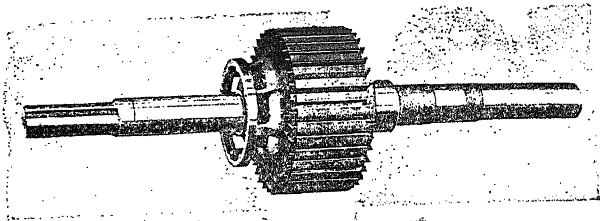

Fig. 132. Small Armature Core Ready for Winding
Courtesy of the Reliance Electric and Engineering Company

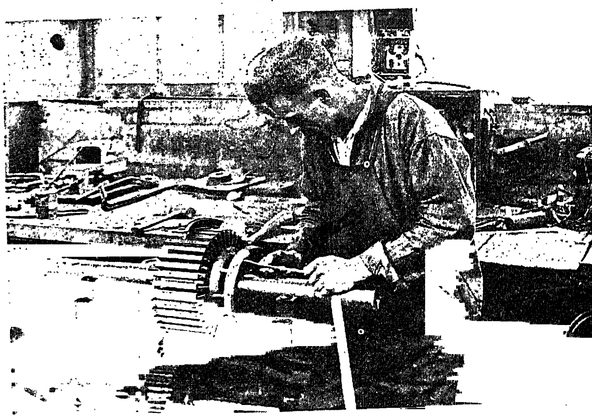

Fig. 133. Insulating the Supporting Ring at the Back End of the Armature
Courtesy of the Reliance Electric and Engineering Company

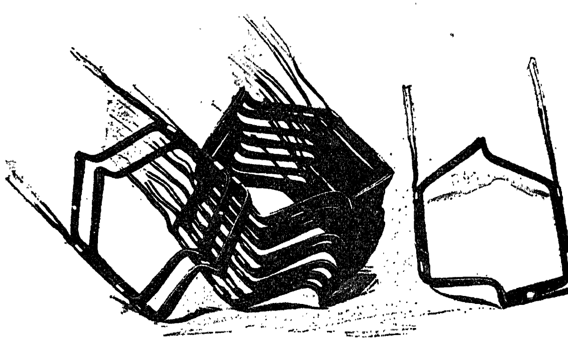

Fig. 134. Form-Wound Coils Ready to be Taped
Courtesy of the Reliance Electric and Engineering Company

shape and cut to the correct length and the ends are placed in the grooves in the top of the commutator risers. A layer of

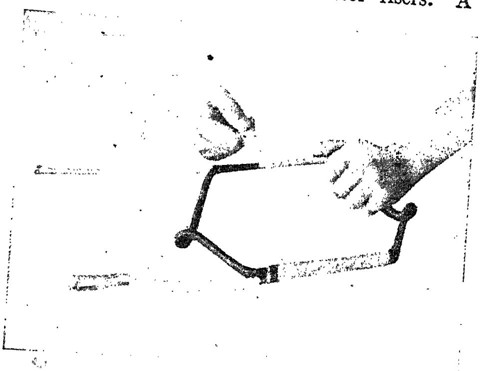

Fig. 135. Taping Coils by Hand
Courtesy of the Reliance Electric and Engineering Company

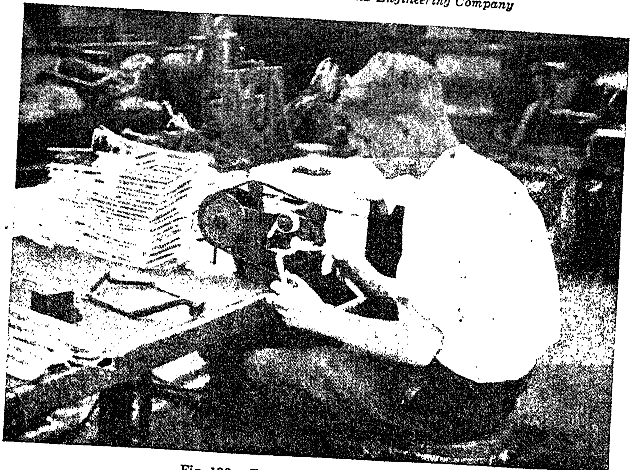

Fig. 136. Taping Coils with a Machine
Courtesy of the Reliance Electric and Engineering Company

insulation is then placed over the lower layer of connections, as shown in Fig. 140, and the upper layer of connections is placed in

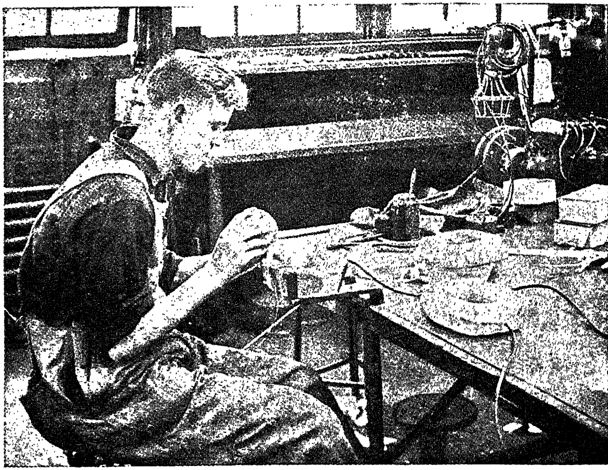

Fig. 137 Taping Field Coils
Courtesy of the Reliance Electric and Engineering Company

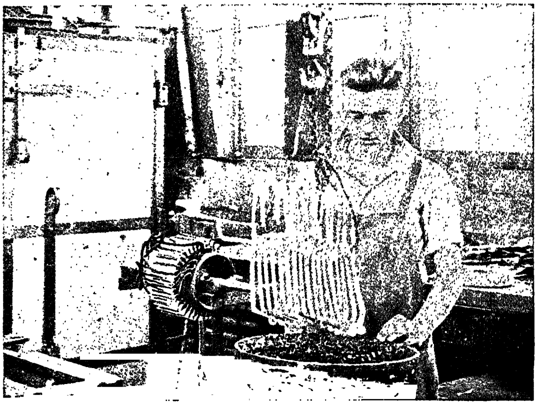

Fig. 138. Dipping Coils in Insulating Compound
Courtesy of the Reliance Electric and Engineering Company

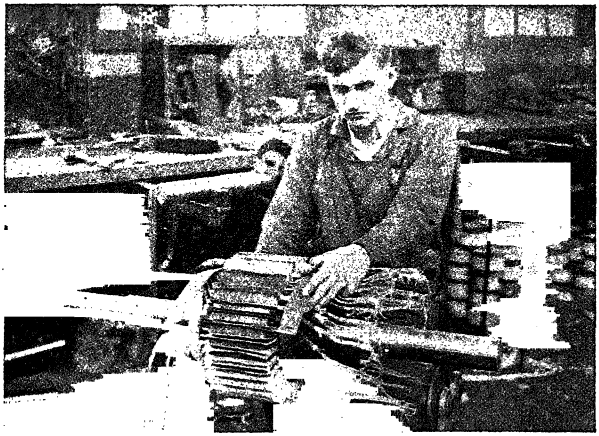

Fig. 139. Placing Coils on the Armature Core
Courtesy of the Reliance Electric and Engineering Company

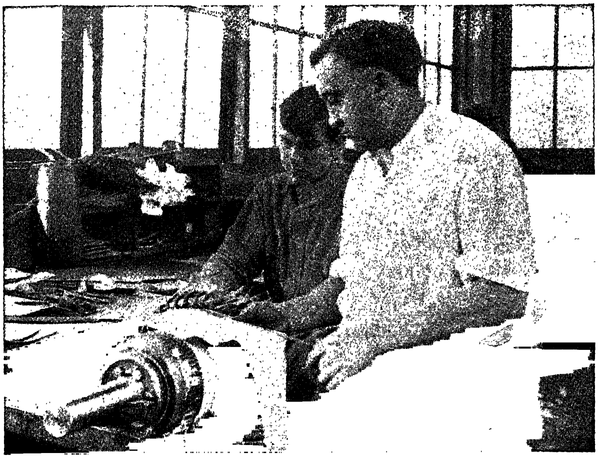

Fig. 140 Placing Insulation over the Lower Layer of End Connections
Courtesy of the Reliance Electric and Engineering Company

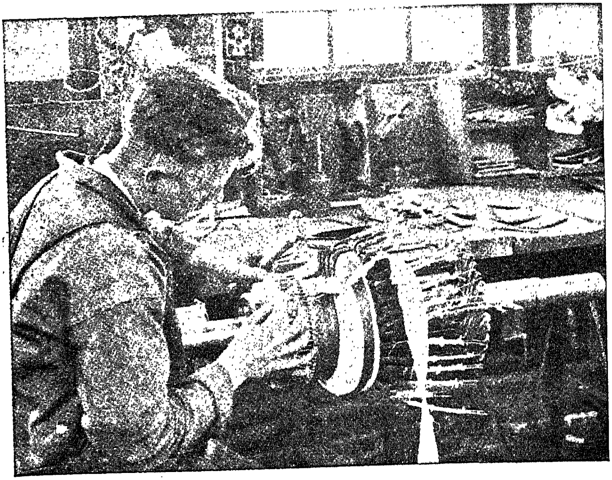

Fig. 141. Placing Upper Layer of Connections in Position
Courtesy of the Reliance Electric and Engineering Company

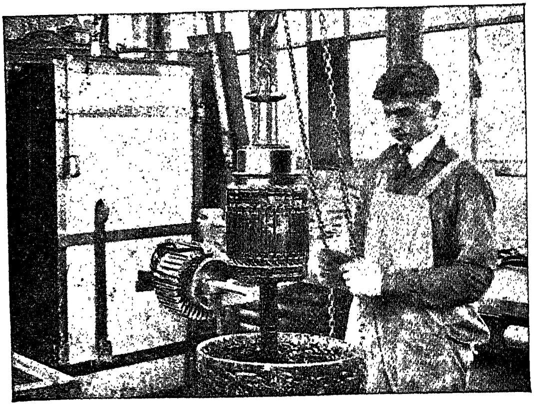

Fig. 142. Dipping Completed Winding in Insulating Compound
Courtesy of the Reliance Electric and Engineering Company

position, as shown in Fig. 141. The ends of the coils are then all soldered to the commutator risers. Wedges are then driven in the tops of the slots over the winding and binding wires placed

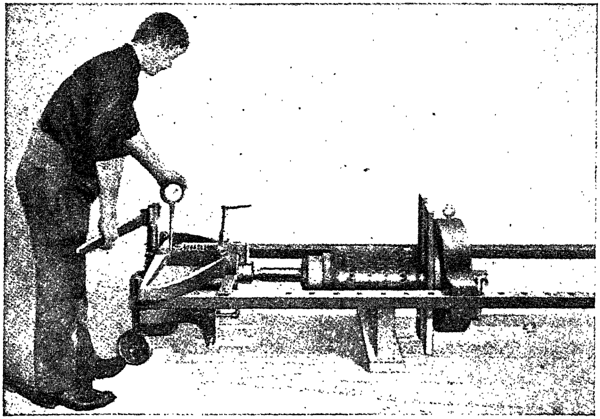

Fig. 143. Adjustable Press for Forcing the Shaft in and out of the Armature
Courtesy of the Reliance Electric and Engineering Company

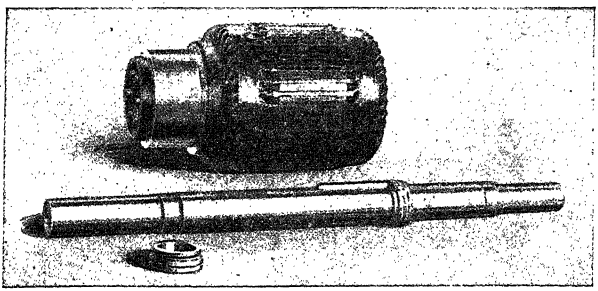

Fig. 144. Completed Armature Core with Shaft Removed
Courtesy of the Reliance Electric and Engineering Company

around the ends of the winding. The completed winding is dipped in insulating compound, as shown in Fig. 142, and baked or allowed to dry.

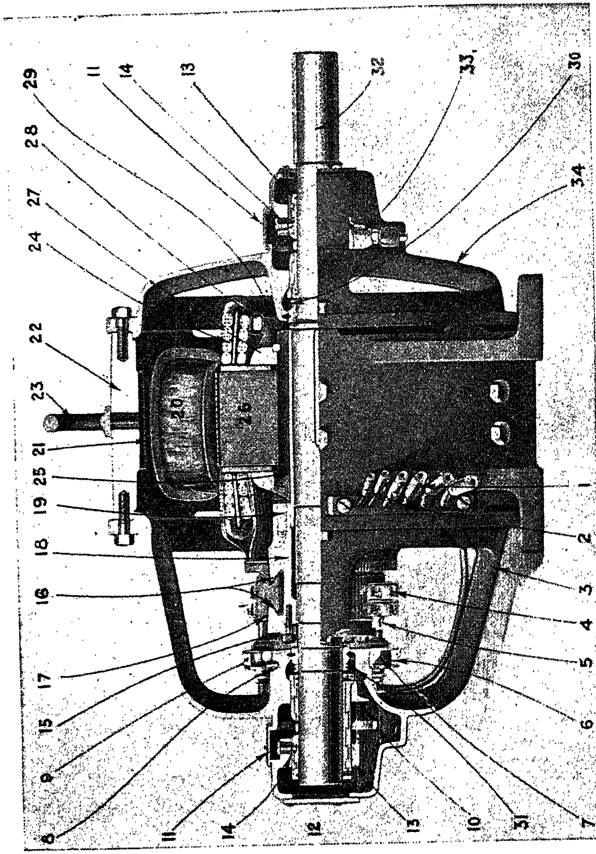

Fig. 145. Partial Cross-Section of a Small Dynamo Showing the Principal Parts

1. Leads and Connectors; 2. Terminal Board; 3. Front Bearing Bracket; 4. Brush Holder 5. Brush-Holder Stud; 6. Brush-Stud Insulation; 7. Brush Yoke; 8. Brush-Yoke Dowel; 9 Bakelite Insulating Washers; 10. Oil Ring; 11. Oil-Hole Cover; 12. Bearing End Cover; 13 Bearing; 14. Bearing Dowel; 15. Commutator Metal V Ring; 16. Commutator Insulating Rings 17. Commutator Segments; 18. Commutator Sleeve; 19. Commutator Key; 20. Field Coil; 21 Field Coil Insulating Washer; 22. Frame; 23. Eye Bolt; 24. Armature Coils; 25. Armatur Spider; 26. Armature Core; 27. Armature End Plate; 28. Armature-Coil Supporting Ring (par of No. 27); 29. Armature End-Plate Key; 30. Oil Throw; 31. Oil Throw; 32. Armature Shaft 33. Oil Overflow; 34. Back Bearing Bracket

An adjustable press for removing and forcing the shaft in place is shown in Fig. 143. A completed armature with the shaft removed is shown in Fig. 144.

A partial cross-section of a small dynamo is shown in Fig. 145, and the names of the principal parts are given below the figure.

Suggestions for Dipping and Baking of Armatures. Dipping the armatures in varnish and then thoroughly baking fills all cracks and pores in the insulation. This greatly reduces the possibility of break-downs which might occur if moisture or other conducting material should get into the cracks. Further, it acts as an effective bond to prevent vibration of the different parts. Dipping and baking of comparatively new armatures is an insurance against maintenance charges for rewinding, etc. It improves the insulation, fills up the pores, keeps a smooth surface on the coils and prevents vibration of armature parts.

Equipment. The following equipment is required: a tank to contain the dipping solution; an oven in which to bake; and means of handling the apparatus.

Cleaning. Remove oil and dirt thoroughly with clean, compressed air. Where oil is excessive use a cloth dampened with benzine. To protect the polished surfaces, such as the journal and the face of the commutator, tape with friction tape. The journal, after dipping, can also be rubbed with a cloth wet with benzine.

Drying. Heat the apparatus in an oven to 100° C. so that, with the delay involved in getting it to the dipping tank, it will be at a temperature of 40° to 60° C. at the time of dipping.

Dipping. Dip in an oil-proof and moisture-proof baking and insulating varnish at approximately the specific gravity listed below. If the varnish is too heavy, thin with benzine.

Specific Gravity of Insulating Varnish. The specific gravities of insulating varnish at the temperature of solution are 0.850 at 15° C.; 0.846 at 20° C.; 0.843 at 25° C., and 0.840 at 30° C.

Dip armatures in the varnish in a vertical position, so that all windings are totally immersed. Allow them to soak until all signs of bubbling cease (20 to 30 minutes).

If a tank is not available, immerse the armature in a pan of varnish, turning the armature at intervals of 20 to 30 minutes. The varnish should be deep enough to cover the slots. Turn

until all the coils have been thoroughly soaked. The insulated creepage surface at the end of the commutator should have repeated paintings of the varnish.

For direct-current machines, the field coils should be removed, dipped, and baked in the same way as the armatures.

For alternating-current machines, dip the frame (the brush-holders having been removed) in a vertical position, rear end down. All windings and connections should be covered. Allow it to remain in the varnish until all bubbling ceases. Do not immerse brush-holder, pads, nor arms.

Draining. Drain at room temperature until all dripping ceases. The apparatus should be placed in such a position that pocketing will not occur.

Baking. Place armatures in vertical position in an oven and bake at 125° C. for the following time: armatures below a 12-inch diameter, 24 hours; armatures of 12- to 30-inch diameter, 36 hours; and armatures over a 30-inch diameter, 48 hours.

If the rotor is baked in a horizontal position, it should be given a half turn every 15 to 30 minutes during the first half of the baking period, otherwise the varnish will drain toward the lower side and throw the armature out of balance.

Place the frames in vertical position in the oven, pinion end down, and bake at 125° C. for the same time as the corresponding size armature.

SOME DON'TS TO BE OBSERVED

Do not use matches; do not smoke; do not use lighted torches, electric hoists or any other device that may produce sparks around the dipping tank, as the varnish is inflammable.

If steam is used for heating, do not permit it to enter the oven, thereby giving the apparatus a vapor bath. This is worse than no dipping.

Do not permit the temperature to exceed 130° C.

Do not rush the baking period. A wet motor is worse than one that has not been treated.

SOME PRECAUTIONS TO BE OBSERVED

Provide for ventilation of the oven, no matter how small it is made; holes near the top and bottom will usually provide natural ventilation. There should be a complete change of air in the oven once every hour.

Provide uniform temperature of air in the oven. Place thermometers at various heights in the oven to determine the temperature.

Turn armatures frequently, if baked horizontally, to prevent unbalancing.

ARMATURE WINDING

PART III

ARMATURE WINDINGS FOR ALTERNATING-CURRENT MACHINES

THEORETICAL CONSIDERATIONS

Generators and Motors. The armature windings for alternating-current generators and motors are essentially alike. For different types of machines there may be a difference in the form of the slots in the armature core, in which the windings are placed, but the same form and arrangement of inductors may be used in every case. In the following discussion particular reference will be made to alternating-current generators in order to make as clear as possible the e.m.f. relations that are involved.

In the case of alternating-current machines either the armature or the magnetic field may be the rotating part of the machine, but it is usually more convenient to make and to understand a winding diagram representing a winding if it represents a revolving armature. The form of the winding may be exactly the same, no matter whether the armature is the rotating or stationary part. In the case of a revolving armature the inductors are placed in slots cut in the outside cylindrical surface of the armature core, while in the case of a stationary armature the inductors are placed in slots cut in the inside cylindrical surface of the stationary structure. The rotating part of the machine is called the rotor and the stationary part is called the stator.

Relation of E.M.F.'s in Simple Alternator. A loop of wire, revolving in a magnetic field, as shown in Fig. 11, constitutes a simple alternating-current generator, and if the magnetic field is uniform in strength the e.m.f. induced in the loop may be represented by a sine curve as shown in Fig. 10. If an alternating-current voltmeter be connected to the terminals of this loop, it will indicate the value of the effective e.m.f. induced in the loop. The value of the effective e.m.f. is numerically equal to the square

root of the average of the squares of the successive instantaneous values during one alternation. For a sine-wave e.m.f. the value of the effective e.m.f. is equal to $1 \div \sqrt{2}$ or 0.707 of the maximum e.m.f. induced in the loop. The average e.m.f. is numerically equal to the average of the successive instantaneous values of the e.m.f. during one complete alternation. For a sine-wave e.m.f. the value of the average e.m.f. is equal to $2 \div \pi$ or 0.636 of the maximum e.m.f. induced in the loop.

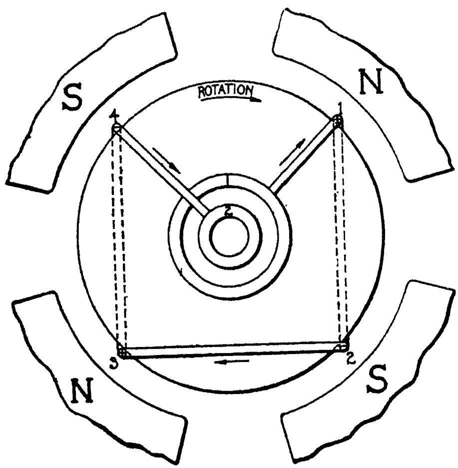

Fig. 146. Single-Phase Winding for Four-Pole Machine, Composed of Single Inductor per Pole

The effective value of an e.m.f. divided by the average value of the e.m.f. gives the value of what is called the form factor of the e.m.f. wave. The form factor for a sine-wave e.m.f. is numerically equal to $0.707 \div 0.636 = 1.11$

Simple Single-Phase Winding. A single-phase concentrated armature winding composed of a single inductor per pole is shown diagrammatically in Fig. 146, and a complete development of the winding is given in Fig. 147. A four-pole magnetic field has been chosen merely on account of simplicity; the principles and operation could be applied and explained equally well for a two-

six-, or eight-pole field, or, in fact, for any even number of poles, but the diagrams would not be so easy to trace. The inductors are shown rotating in a clockwise direction and when they are moving under the north magnetic poles there will be an e.m.f. induced in them whose direction is away from the observer; and while the inductors are moving under the south magnetic poles, there will be an e.m.f. induced in them whose direction is toward the observer. The plus (+) signs indicate an e.m.f. away from the observer, and the minus (−) signs an e.m.f. toward the observer.

Effective E.M.F. of Winding. The mechanical construction of the different magnetic poles is assumed to be the same and the

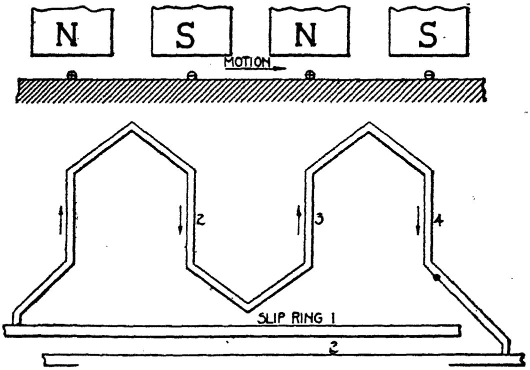

Fig. 147. Development of Winding Shown in Fig. 146

armature is assumed to be centrally located. This will result in the same magnetic flux distribution under all the different poles. The inductors are all spaced an equal distance apart so that they occupy exactly corresponding positions under the different poles at any given instant. Hence the e.m.f.'s induced in all the inductors reach their maximum values at the same time, then pass through zero value at the same time, that is, they are all passing through corresponding phases of their respective cycles at the same time, or they are in phase with each other.

In the developed diagram shown in Fig. 147, the four inductors are shown connected in series in such a manner that the

e.m.f.'s add together to produce the total e.m.f. that exists between the slip rings. A continuous electrical connection is established between the winding and the outside circuit by means of brushes which rest upon the slip rings. The form of the resultant e.m.f. wave will be exactly the same as the form of the e.m.f. wave for any one of the inductors, as they are all identical and exactly in phase with one another. The maximum value of the resultant e.m.f. wave will be equal to the sum of the maximum values of the four component waves. The effective e.m.f. of the entire winding will be equal to the arithmetical sum of the effective e.m.f.'s in the four inductors, and the average e.m.f. of

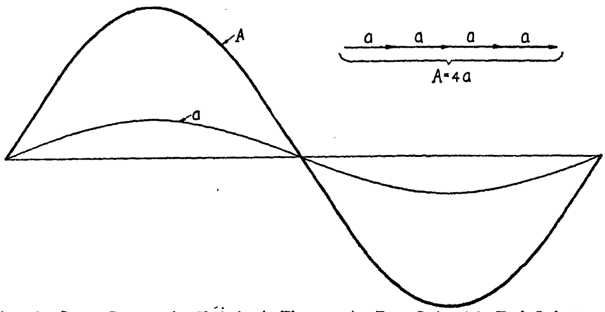

Fig. 148. Curves Representing Variation in Electromotive Force Induced in Each Inductor of Winding Shown in Fig. 146 and Total Electromotive Force between Slip Rings

the entire winding will be equal to the sum of the average e.m.f.'s in the four inductors.

Form Factor. The form factor of the e.m.f. wave will depend upon the distribution of the magnetic flux under the different poles. The ideal distribution of magnetic flux is one which results in what is called a sine-wave e.m.f. being induced in the inductors as they are made to move in the magnetic field.

Assuming there is an e.m.f. induced in each of the inductors as represented by the curve *a* in Fig. 148, then the e.m.f. between the collector rings may be represented by a curve *A*, whose ordinate at any instant is four times the ordinate of the curve *a* at the same instant. In general the ordinate of the resultant curve *A* will be as many times the ordinate of the curve *a* as there are inductors in series.

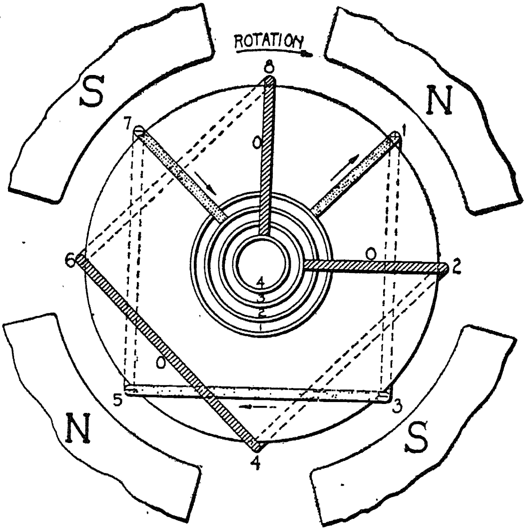

Fig. 149. Two-Phase Winding for Four-Pole Machine, Composed of Single Inductor per Phase per Pole

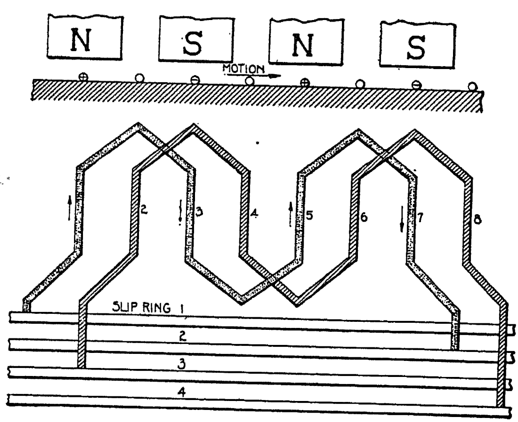

Fig. 150. Development of Winding Shown in Fig. 149

Simple Two-Phase Winding. A two-phase concentrated armature winding composed of a single inductor per phase per pole is shown diagrammatically in Fig. 149, and a complete development of the winding is given in Fig. 150. Four inductors are connected in series between the slip rings *1* and *2* and these inductors are equally spaced around the surface of the armature and connected in such a manner that the e.m.f.'s induced in them are all in phase and acting in the same direction with respect to the slip rings. The four remaining inductors are, likewise, connected in series between the slip rings *3* and *4* and they are equally spaced around the surface of the armature and connected in such a manner that the e.m.f.'s induced in them are all in phase and acting in the same direction with respect to the slip rings. The e.m.f. between slip rings *1* and *2*, and the e.m.f. between slip rings *3* and *4*, will be displaced in phase with respect to each other by 90 degrees.

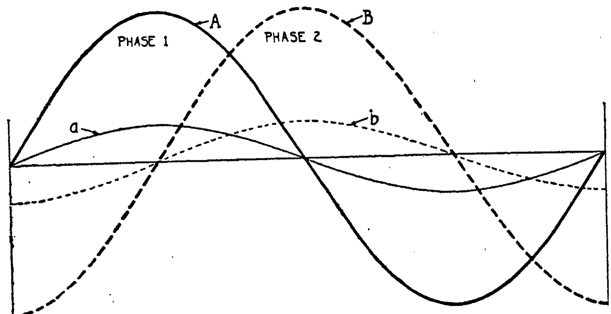

Fig. 151. Curves Representing Variation in Electromotive Force Induced in Each Inductor of Winding Shown in Fig. 149 and Total Electromotive Force between Slip Rings

Effective E.M.F. of Winding. The e.m.f. induced in each of the inductors connected between slip rings *1* and *2* may be represented by the curve *a* in Fig. 151, and, since there are four inductors in series, the total e.m.f. between the slip rings *1* and *2* may be represented by curve *A*. The ordinates of curve *A* are four times the ordinates of curve *a*, since the e.m.f. induced in each of the four inductors has the same value and they are all in phase with each other. Likewise, the e.m.f. induced in each of the

inductors connected between slip rings *3* and *4* may be represented by a curve *b*, Fig. 151, and the total e.m.f. between slip rings *3* and *4* by curve *B*. The e.m.f. induced in the inductors between slip rings *1* and *2* will be displaced in phase by 90 degrees from the e.m.f. induced in the inductors between slip rings *3* and *4*, owing to the relative location of the inductors on the surface of the armature; this fact is represented graphically in Fig. 151, by drawing curves *A* and *B* 90 degrees apart.

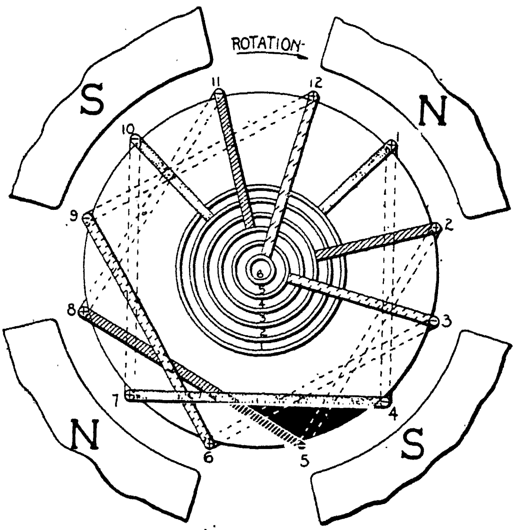

Fig. 152. Three-Phase Winding for Four-Pole Machine, Composed of Single Inductor per Phase per Pole

Simple Three-Phase Winding. A three-phase concentrated armature winding composed of a single inductor per phase per pole is shown diagrammatically in Fig. 152, and a complete development of the winding is given in Fig. 153. Four inductors are connected in series in each of the three electrically independent circuits. The four inductors in each circuit are equally spaced around the armature surface and so connected that the e.m.f.'s induced in them all act in the same direction with respect to the

slip rings forming the terminals of the circuit. The inductors forming the three electrically independent circuits are distributed

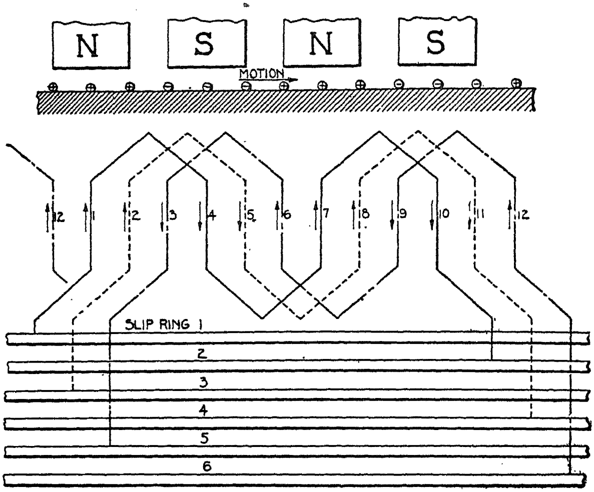

Fig. 153. Development of Winding Shown in Fig. 152

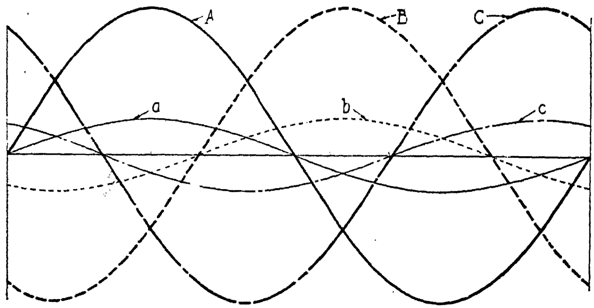

Fig. 154. Curves Representing Variation in Electromotive Force in Each Inductor of Winding Shown in Fig. 152 and Total Electromotive Force between Slip Rings

over the armature surface in such a manner that the e.m.f.'s induced in the three circuits are displaced in phase with respect

to each other by 120 degrees. The relation of these e.m.f.'s is shown in Fig. 154, by the curves marked *A*, *B*, and *C*, which are displaced from each other by 120 degrees. The ordinate of each of these curves is four times the ordinate of the smaller curves *a*, *b*, and *c*.

Electrical Degrees. The e.m.f. curve of an alternator is usually represented by a sine curve and completes one cycle in 360 degrees, as shown in Figs. 148 and 151. This cycle is com-

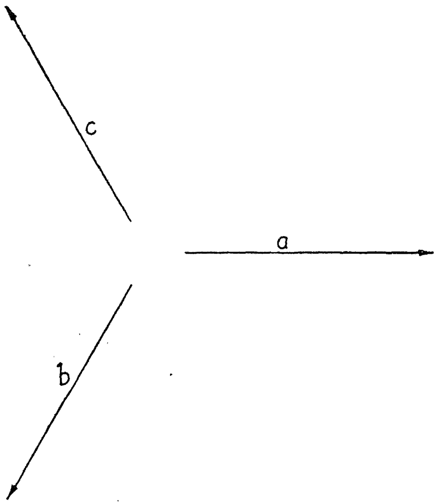

Fig. 155. Three Vectors Representing Three Equal Electromotive Forces or Currents Displaced in Phase with Respect to Each Other by 120 Degrees

pleted while the armature moves, relative to the poles, through a distance equal to twice the pole pitch, and it is customary and very convenient to call this distance 360 electrical degrees. In a two-pole machine each revolution corresponds to 360 electrical degrees; in a four-pole machine each revolution corresponds to 720 electrical degrees; in a six-pole machine each revolution corresponds to 1080 electrical degrees, etc. In general, the number of

electrical degrees will be equal to the product of the pairs of poles by 360.

Y Connections. It will be seen from Figs. 152 and 153 that a three-phase winding requires six leads, two for each phase. It is usual, however, to connect certain of these leads together so that only three leads have to be brought out and connected to the load.

The e.m.f.'s induced in the three windings are displaced in phase from each other by 120 degrees and may be represented by

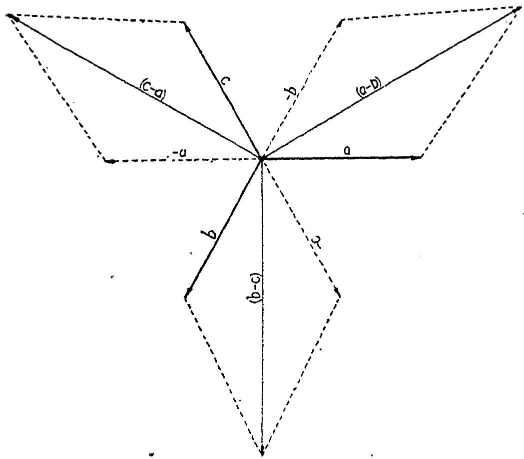

Fig. 156. Vector Diagram for Three-Phase Y Connections

three vectors *a, b,* and *c,* as shown in Figs. 155 and 156. The three windings in which the e.m.f.'s are induced may be connected as indicated in Fig. 157. In this type of connection, called a Y connection, one end of each of the three windings is connected to the common junction point, which is called the neutral, and the remaining three ends are connected to slip rings, which in turn are connected to the external circuit by means of the brushes. In some cases an additional slip ring is provided and the neutral is connected to it so that an outside connection may be made to the neutral. The positive direction of the e.m.f.'s is taken as being

away from the neutral point as represented by the arrows along the windings. Each of the three windings will carry the same current at any instant as is carried by the line wire connected to the end of that winding by means of the brush and slip ring. Thus the current in line *3* at any instant will be the same as the current in winding *c* at that same instant, etc.

The voltage between any two of the lines is the vector sum of the voltages induced in the two windings connected between the two lines. Thus the voltage acting around the circuit from line *1* through the load connected between lines *1* and *2*, through

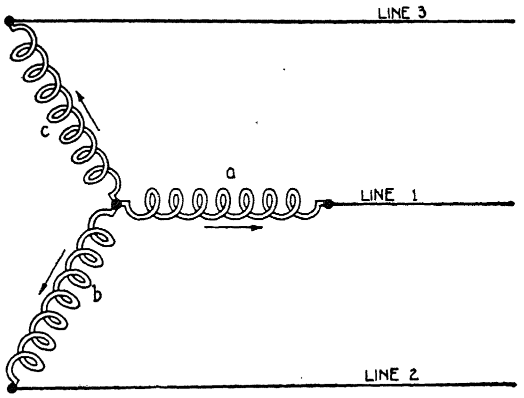

Fig. 157 Y-Connected Armature Winding

winding *b* to the neutral, through winding *a* and back to line *1* will be equal to the e.m.f. in winding *a* minus the e.m.f. in winding *b*, since the e.m.f. in winding *b* is acting around the circuit in a direction opposite to the direction traced through above. In subtracting one vector from another, merely reverse the direction of the vector you wish to subtract and then add them. Thus in subtracting vector *b* from vector *a* in Fig. 156 you draw the vector *b* in an exactly opposite direction and call it $-b$ and then adding vectors *a* and $-b$ gives the vector $a-b$. Vector $b-c$ represents the e.m.f. acting on the load connected between lines *2* and *3* and in a direction from line *2* to line *3*. Likewise,

vector $c-a$ represents the e.m.f. acting on the load connected between lines *3* and *1* and in a direction from line *3* to line *1*.

Assuming there are equal e.m.f.'s induced in each of the three windings, then the value of the e.m.f. between any two lines will be equal to the $\sqrt{3}$ or 1.732 times the e.m.f. in any one of the windings.

Δ Connections. The three windings in which the e.m.f.'s are induced may be connected as shown in Fig. 158. In this type of connection, which is called a Δ (delta) connection, the three windings are connected end to end and form a closed circuit. The junction points of the windings are connected to slip rings, which in turn are connected to the three lines by means of brushes.

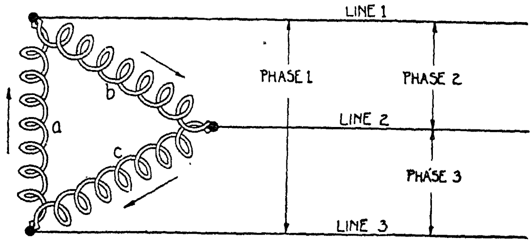

Fig. 158. Delta-Connected Armature Winding

The positive direction of the e.m.f.'s is taken as being clockwise, as indicated by the three arrows along the windings in Fig. 158. The e.m.f. between any two lines will be equal to the e.m.f. induced in the winding connected directly between the two lines. Thus, the e.m.f. between lines *1* and *3* is equal to the e.m.f. induced in winding *a*, the e.m.f. between lines *2* and *1* is equal to the e.m.f. induced in winding *b*, etc.

The current in any one of the lines is a combination of the currents in two of the windings. Thus, the current in line *1* is a combination of the currents in windings *a* and *b*. The current in winding *a* is toward line *1* and the current in winding *b* is away from line *1*, so the current in winding *b* must be subtracted from the current in winding *a* in order to obtain the value of the current in line *1*. The three currents in the three windings,

assuming they are all equal, may be represented by three equal vectors, such as a, b, and c, as shown in Fig. 159. The current in line *1* will be equal to $a-b$, the current in line *2* will be equal to $b-c$ and the current in line *3* will be equal to $c-a$, as shown in the figure. The numerical value of the current in any line, assuming the currents in the three windings are equal, will be equal to $\sqrt{3}$, or 1.732 times the current in any one of the windings.

Voltage and Current Relation in a Two-Phase Winding. The simple two-phase winding shown in Fig. 149, requires four slip

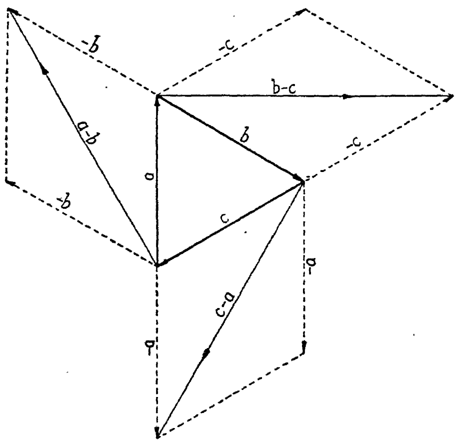

Fig. 159. Vector Diagram for Three-Phase Delta-Connection

rings, and each of the windings has independent electrical connections to the outside or load circuits. One of these four slip rings may be omitted by joining one end of each of the two windings and then connecting this junction to a slip ring which will serve for both windings, as shown in Fig. 160.

The e.m.f. between line *1* and the neutral will be equal to the e.m.f. induced in the winding a, and the e.m.f. between line *2* and the neutral will be equal to the e.m.f. induced in winding b. The e.m.f. acting from line *1* to line *2* through windings b and a back to line *1* is equal to the e.m.f. in winding a minus

the e.m.f. in winding *b*, because in tracing around the above circuit you pass through the winding *a* in the direction of the e.m.f. induced in it and through the winding *b* in the opposite

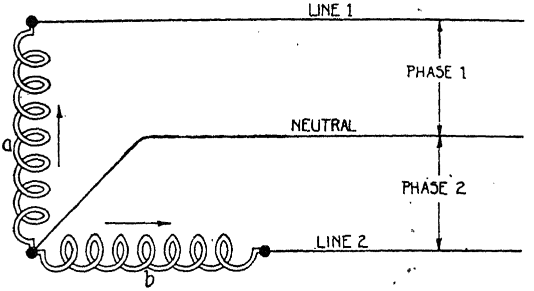

Fig. 160. Three-Wire Two-Phase Winding

direction to the e.m.f. induced in it. The subtraction of the e.m.f. in winding *b* from the e.m.f. in winding *a* is shown in Fig. 161, and the result is represented by the vector marked $a-b$.

The current in line *1* is exactly the same as the current in winding *a*, and likewise, the current in line *2* is exactly the same as the current in winding *b*. The current in the neutral wire is

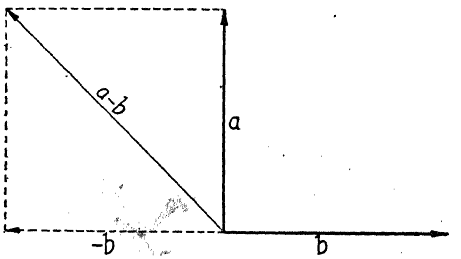

Fig. 161. Vector Diagram of Electromotive Forces for Two-Phase Connection Shown in Fig. 160

equal to the vector sum of the currents in the two windings Ia and Ib, as shown in Fig. 162, in which $Ia+Ib$ represents the neutral current. In Fig. 162 the currents in lines *1* and *2* are

assumed to be equal and in phase with their respective e.m.f.'s. A vector diagram is given in Fig. 163 in which the currents in lines *1* and *2* are unequal, and the currents in the two windings are displaced in phase from the e.m.f.'s by angles θ_1 and θ_2 respectively. A counterclockwise direction of rotation is considered as being positive. The neutral current is equal to $Ia+Ib$, as shown in the figure. A two-phase "star" connection is shown in Fig. 164. In this type of connection, the middle points of each of the two phases are joined, and the four sides are brought out to four slip rings. This connection is equivalent to what might be called a four-phase system. A two-phase mesh connection is shown in Fig. 165. This is a form of closed-circuit winding, as will be explained in one of the following sections.

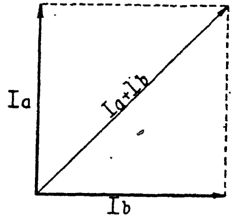

Fig. 162. Vector Diagram of Currents for Two-Phase Connection Shown in Fig. 160. Balanced Load, Unity Power Factor

Concentrated and Distributed Armature Windings. *Distinction Between.* A concentrated armature winding, as its name indicates, is one in which all the inductors per phase per pole are grouped in a single slot or in a single bundle on the surface of the armature. The windings whose developments are given in Figs. 147, 150, and 153 are all of the concentrated type and in each of these there is a single inductor per phase per pole.

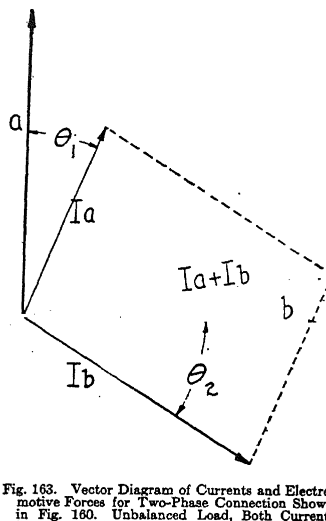

Fig. 163. Vector Diagram of Currents and Electromotive Forces for Two-Phase Connection Shown in Fig. 160. Unbalanced Load, Both Currents Lagging by Different Angles

Parts of the developed diagrams of two different forms of single-phase distributed windings having six inductors per phase

per pole are given in Figs. 166 and 167. In each of these windings the e.m.f.'s induced in adjacent inductors are displaced in phase from each other by 30 electrical degrees.

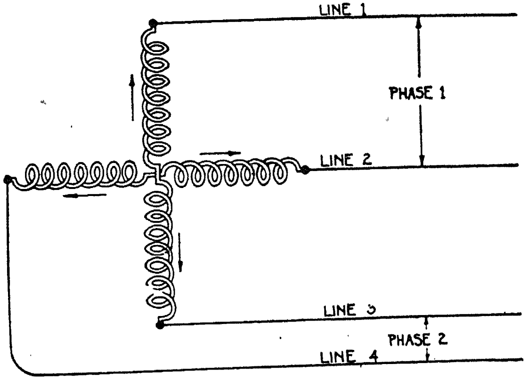

Fig. 164. Star-Connected Two-Phase System

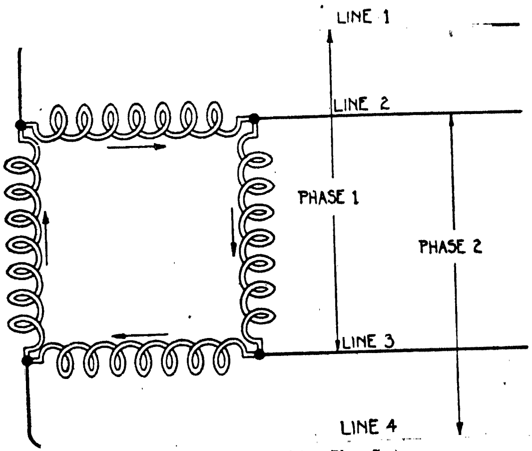

Fig. 165. Mesh-Connected Two-Phase System

In Fig. 166 the e.m.f. induced in the band of inductors composed of numbers *1*, *2*, *3*, *4*, *5*, and *6*, which will be referred

to as band *1*, acts in series with the e.m.f. induced in the band of inductors composed of numbers *7*, *8*, *9*, *10*, *11*, and *12*, which

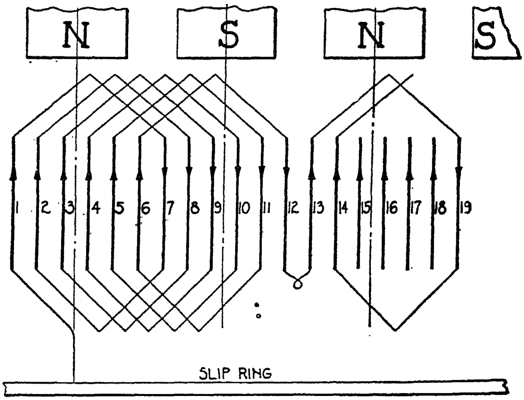

Fig. 166. Portion of Uniformly Distributed Single-Phase Armature Winding, Six Slots per Pole

will be referred to as band *2*. The e.m.f. in each of these bands of inductors is equal to the vector sum of the e.m.f.'s in the inductors composing the band. Thus in band *1*, the total e.m.f. can be

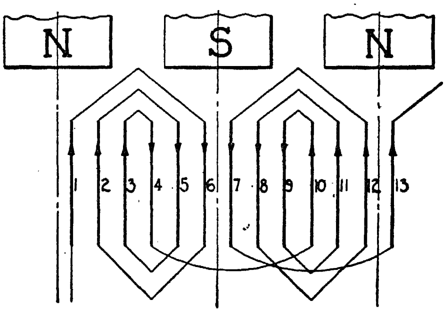

Fig. 167 Portion of Uniformly Distributed Single-Phase Armature Winding, Six Slots per Pole

obtained as shown in Fig. 168. The e.m.f induced in each of the inductors is represented by the letter *e*, and there are six of

them, which, when combined, give the value of the resultant e.m.f. E_1. This resultant e.m.f. is equal to 0.64 of $6e$; that is, the total e.m.f. produced by the six inductors per pole when

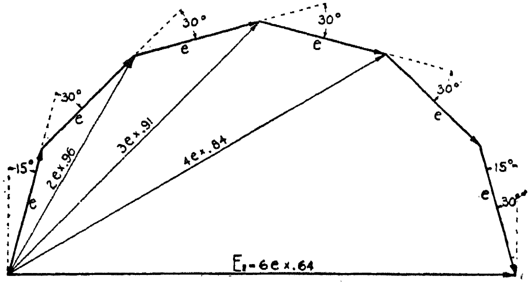

Fig. 168. Vector Addition of Equal Electromotive Forces Displaced in Phase with Respect to Each Other by 30 Electrical Degrees

uniformly distributed is equal to 0.64 of the e.m.f. that the same number of inductors would give if they were all located at the same point on the surface of the armature. The e.m.f. induced in the second band can be determined in exactly the same manner as that used for the first band. Now if the centers of these two bands are exactly 180 electrical degrees apart the resultant e.m.f.'s for the different bands may be added to obtain the total e.m.f.

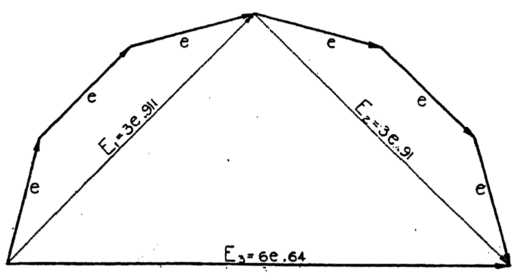

Fig. 169. Vector Addition of Electromotive Forces Displaced in Phase with Respect to Each Other by 30 Electrical Degrees

If the bands are not 180 electrical degrees apart then the e.m.f.'s induced in them must be added by means of vectors which will take care of the difference in phase.

In Fig. 167 band *1* is composed of inductors *1*, *2*, and *3*; band *2* is composed of inductors *4*, *5*, and *6*. The e.m.f. induced in band *1* is equal to E_1 in Fig. 169, and the e.m.f. induced in band *2* is equal to E_2. These two bands are displaced in phase by 90 electrical degrees, so that E_1 and E_2 must be added vectorially and the resultant E_3 is equal to 0.64 of $6e$ which is exactly the same as the resultant E for one of the bands in Fig. 166. An armature wound as shown in Fig. 166 will have as many bands as there are poles and one wound as shown in Fig. 167 will have twice as many bands as poles. The resultant e.m.f. for the entire winding will be numerically the same in both cases.

Comparison of Concentrated and Distributed Windings. The e.m.f. induced in an armature winding when composed of a number of inductors distributed over the surface of the armature is less than the e.m.f. induced in an armature winding composed of the same number of inductors but concentrated in one slot or bundle per phase per pole. The distributed winding, however, possesses the great advantage of affording a means of controlling the resultant wave form, while in the concentrated winding the wave form is dependent upon the manner in which the magnetic flux is distributed under the magnetic poles.

When the winding is concentrated, the number of turns per coil is increased; and since the inductance of a coil increases as the square of the number of turns, the reactance of a concentrated winding is much greater than the reactance of a distributed winding. The result is that the concentrated winding gives poorer voltage regulation.

Development of Electromotive-Force Equation. In the developed windings given in Figs. 147, 150, and 153, the inductors that are connected together are displaced from each other by an exact pole pitch, and such windings are called full-pitch windings. In a full-pitch winding, all the inductors that are connected in series have e.m.f.'s induced in them which are in phase with each other, and the total e.m.f. between collector rings is equal to Ne. N stands for the number of inductors in series and e for the e.m.f. induced in each inductor.

Average Electromotive Force. The average e.m.f. induced in each inductor will be equal to the magnetic lines cut by the

inductor in one second divided by 10^8. The flux per pole ϕ multiplied by the number of poles p, and this product multiplied by the number of revolutions per second that the inductor makes, will give the value of the flux cut by each inductor per second. The above statements may be written in the form of an equation as follows:

$$e_{av}=\phi\times p\times \text{r.p.s.}\times 10^{-8}$$

in which e_{av} stands for the average e.m.f. If the e.m.f. induced in the inductors follows a sine law, then the effective e.m.f. will be equal to 1.11 times the average e.m.f., and the following equation may be written giving the value of the effective e.m.f. e.

$$e=1.11\times\phi\times p\times \text{r.p.s.}\times 10^{-8}$$

Total Electromotive Force. If there are N inductors in series

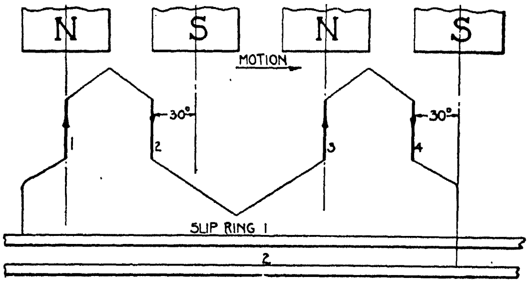

Fig. 170. Short-Pitch, Concentrated, Single-Phase Armature Winding

in each circuit and the e.m.f.'s are in phase, the total e.m.f. E will be given by the following equation:

$$E=N\times 1.11\times\phi\times p\times \text{r.p.s.}\times 10^{-8}$$

Since

$$\text{r.p.s.}\times\frac{p}{2}=f,$$

then

$$\text{r.p.s.}\times p=2f;$$

and the above equation may be written as follows:

$$E=N\times 2.22\times\phi\times f\times 10^{-8}$$

This equation gives the value of the e.m.f. per phase for a full-pitch concentrated winding. Each of the small lines a in Fig. 148 represents the e.m.f. induced in each of the inductors, and since these e.m.f.'s are all in phase, the line A, which represents the total e.m.f., will be equal to four times the length of any one of the shorter lines a.

E.M.F. for Short-Pitch Windings. Now supposing the inductors composing the winding be arranged in such a way that they are no longer displaced from each other by an exact pole pitch, as shown in Fig. 170. In this case the inductors in each coil are 150 electrical degrees apart instead of 180 degrees, as shown in Fig. 147. A winding of this kind is called a short-pitch winding. The e.m.f. induced in each of the four inductors will have the same value as in Fig. 147, but they will not all be in phase with one another. The four e.m.f.'s are shown in their proper phase relation to each other in Fig. 171 by the four small vectors marked e_1, e_2, e_3, and e_4. These four e.m.f.'s combined give the value of the resultant e.m.f. E. The e.m.f. induced in each coil is equal to 2 times the e.m.f. in one of the half coils multiplied by the cosine of the angle θ that the coil lacks of being full pitch. The e.m.f. equation for a short-pitch concentrated winding is as follows:

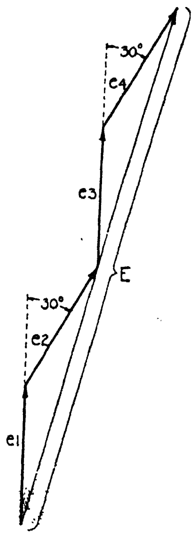

Fig. 171. Vector Addition of Electromotive Forces for Short-Pitch Armature Winding

$$E = N \times (2.22 \times \phi \times f \times 10^{-8}) \times \cos\frac{\theta}{2}$$

The part of this equation inside the parenthesis represents the value of the e.m.f. induced in each of the half coils.

E.M.F. for Distributed Windings. In distributed windings such as the ones shown in Figs. 166 and 167, it is necessary first to determine the resultant e.m.f. induced in each of the bands of inductors and then add these results vectorially. Each band in Fig. 166 is composed of six half coils, 30 degrees apart, and the centers of these bands are 180 electrical degrees apart, so that the

e.m.f.'s in the different bands are in phase, when properly connected as shown in the figure. The e.m.f. in a single band is given by the vector diagram shown in Fig. 168, and is equal to .64 of the arithmetical sum of the six equal component e.m.f.'s. The factor by which the arithmetical sum of the e.m.f.'s in any band must be multiplied in order to get the value of the effective e.m.f. is called the distribution factor. Thus in Fig. 166 the distribution factor is .64 and in Fig. 167 it is .911. In a four-pole machine with a winding like the one shown in Fig. 166 there will be four bands, and in the case of a four-pole machine with a winding like the one shown in Fig. 167 there will be 8 bands. The same e.m.f. will be induced in both these windings under identical conditions, as shown by the following equations:

$$\begin{aligned} E &= 4\times(6e\times.64)\times 1 \text{ (for winding in Fig. 166)} \\ &= 24\times.64\times e \\ &= 15.36e \end{aligned}$$

$$\begin{aligned} E &= 8\times(3e\times.911)\times\cos\frac{90}{2} \text{ (for winding in Fig. 167)} \\ &= 24\times.911\times.707\times e \\ &= 15.36e \end{aligned}$$

This same process of reasoning can be followed in calculating the e.m.f. induced in each phase of any type of winding.

Values of Distribution Factor. The value of the distribution factor for any winding will depend upon the number of slots per phase per pole and the number of these slots that are actually used. The distribution factor will also depend upon the manner in which the inductors are distributed in the slots that are actually used. Thus in a concentrated winding the value of the distribution factor is equal to unity, as all of the inductors composing each phase are located in a single slot per phase per pole.

Single-Phase Windings. In a single-phase winding having two slots per phase per pole the e.m.f. induced in the inductors in the two slots will be displaced in phase from each other by 90 electrical degrees, assuming the slots are equally spaced around the surface of the armature. If each slot contains the same number of inductors, then the same resultant e.m.f. will be induced in each slot, and these two e.m.f.'s combined vectorially will give a

resultant e.m.f. equal to 707 times the sum of the component e.m.f.'s.

If three equally spaced slots be used per phase per pole, and the winding is uniformly distributed in the three slots, then the resultant e.m.f. will be equal to the vector sum of three equal e.m.f.'s which are displaced in phase with respect to each other by 60 electrical degrees. The numerical value of the resultant is equal to .662 times the sum of the component e.m.f.'s.

If there are four slots per phase per pole and the winding is uniformly distributed in these slots, the resultant e.m.f. will be equal to .653 times the sum of the e.m.f.'s induced in the inductors in the different slots.

If there are six slots per phase per pole and the winding is uniformly distributed, the resultant e.m.f. will be equal to .64 times the sum of the e.m.f.'s induced in the six slots.

Two-Phase Windings. In a two-phase winding having two slots per phase per pole and the winding distributed uniformly in the slots, there will be equal e.m.f.'s induced in adjacent slots, which belong to one of the phases, and these e.m.f.'s will be displaced in phase by 45 electrical degrees. The value of the resultant of these two e.m.f.'s will be equal to .924 times their sum. In a two-phase winding having three slots per phase per pole, there will be three e.m.f.'s per phase per pole that are in series and displaced in phase by 30 electrical degrees, and the numerical value of the resultant is equal to .911 times the sum of the three components.

Three-Phase Windings. In a three-phase winding having two slots per phase per pole, there will be two e.m.f.'s per pole that are in series and displaced in phase by 30 electrical degrees. The resultant of these two e.m.f.'s is equal to .966 times their sum.

The values of the distribution factor as given in Table VII are based upon the same number of inductors being placed in each of the slots and all of the slots being used.

Rating of Alternators. The maximum voltage that an alternator can develop continuously depends upon the permissible value of the flux per pole, and the maximum current is limited by the armature copper loss which, along with the core loss, heats the machine. With the value of the voltage and current fixed,

TABLE VII

Distribution Factors for Single-, Two-, and Three-Phase Windings

Slots per Phase per Pole	Distribution Factor		
	Single-Phase	Two-Phase	Three-Phase
1	1.000	1.000	1.000
2	0.707	0.924	0.966
3	0.663	0.911	0.960
4	0.653	0.906	0.958
6	0.644	0.903	0.956

the kilowatt rating depends upon the power factor of the load. The power factor is a variable quantity, and beyond the control of the builder of the machine, so that an alternator is usually rated by giving the product of the volts and amperes, which is called the volt-ampere rating, and this quantity divided by 1000 gives the rating in kilovolt amperes.

Effect of Number of Phases on Rating of Alternator. Consider an armature having six slots per pole and imagine a fixed number of inductors placed in each of the six slots and connected for single-, two-, and three-phase operation, then the following voltages per phase will be obtained:

Number of Phases	Voltage per Phase
Single (all slots used)	Constant $\times 6e \times 0.64$
Single ($\frac{2}{3}$ of slots used)	Constant $\times 4e \times 0.84$
Two	Constant $\times 3e \times 0.91$
Three	Constant $\times 2e \times 0.96$

In the above expressions for voltage, e represents the total e.m.f. induced in the inductors in any one of the slots.

Since there are the same number of inductors in each of the slots, the inductors will all have the same cross-section and therefore carry the same current which we will represent by I_c. The volt-ampere rating, which is equal to the volts per phase times the current per phase times the number of phases, is given as follows:

Number of Phases	Volt-Ampere Rating
Single (all slots used)	Constant $\times 6e \times 0.64 \times 1 \times I_c =$ a constant $\times 0.64$
Single ($\frac{2}{3}$ of slots used)	Constant $\times 4e \times 0.84 \times 1 \times I_c =$ a constant $\times 0.56$
Two	Constant $\times 3e \times 0.91 \times 2 \times I_c =$ a constant $\times 0.91$
Three	Constant $\times 2e \times 0.96 \times 3 \times I_c =$ a constant $\times 0.96$

From the above relations, it is seen that the two- and three-phase ratings are practically the same, although the three-phase rating is the better. The single-phase machine is usually given 65 per cent of the rating of a three-phase machine when all the slots are used.

Classes of Armature Windings for A.-C. Machines. Alternating-current machines are built in many different forms, and many different kinds of armature windings are required to meet the different conditions of operation. The different forms of armature windings may be classified as follows:

(1) **With respect to form of armature**
- (a) Revolving armature
- (b) Stationary armature

The armature of a generator or motor is the part of the machine in which an e.m.f. is induced owing to a relative movement of a magnetic field and the inductors composing the armature winding. When the inductors are mounted on the revolving part of the machine the armature is known as a revolving armature, and when the inductors are mounted on the stationary part of the machine the armature is known as a stationary armature.

(2) **With respect to method of advancing around armature in tracing through winding**

(a) Lap winding	(c) Progressive winding
(b) Wave winding	(d) Retrogressive winding

A lap winding is one in which you advance around the armature in opposite directions at the front and back ends of the armature as you trace through the winding. A three-phase, lap-wound armature is shown in Fig. 172.

A wave winding is one in which you advance around the armature in the same direction at the front and back ends of the armature as you trace through the winding. A three-phase, wave-wound armature is shown in Fig. 173.

A progressive type of winding is shown in Fig. 174. It will be observed that after tracing through inductors *1*, *3*, *5*, and *7* you advance more than a full pole pitch to inductor *2* then around the armature again to slip ring *2*.

A retrogressive type of winding is shown in Fig. 175. It will be observed that after tracing through inductors *2*, *4*, *6*, and *8*,

you advance less than a full pole pitch to inductor *1* then around the armature again to slip ring *2*.

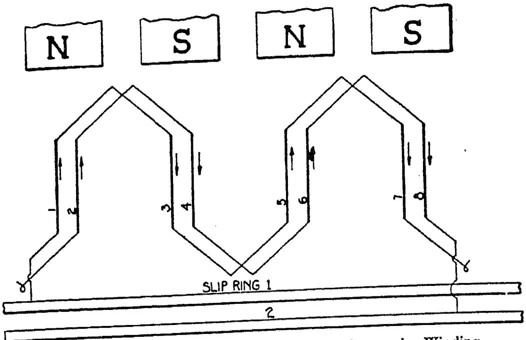

Fig. 174. Developed Diagram of Single-Phase Progressive Winding

(3) **With respect to relation between number of poles and number of coils**

(a) Half-coil windings
(b) Whole-coil windings

A half-coil, or hemitropic, winding is one in which there is one coil group per phase per pair of poles. A single-phase, half-coil

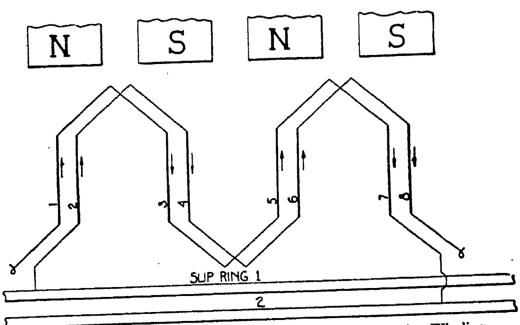

Fig. 175. Developed Diagram of Single-Phase Retrogressive Winding

winding for a four-pole machine is shown in Fig. 176, and a development of the winding is given in Fig. 177. Each of the coil

groups in Figs. 176 and 177 is composed of two coils, one inside of the other and connected in series.

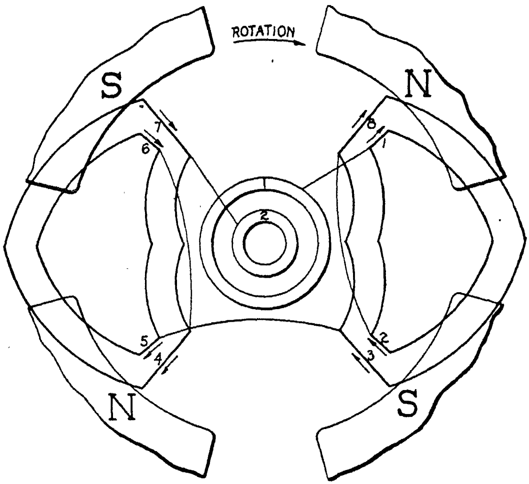

Fig. 176. Radial Diagram of Single-Phase Half-Coil Winding for Four-Pole Machine

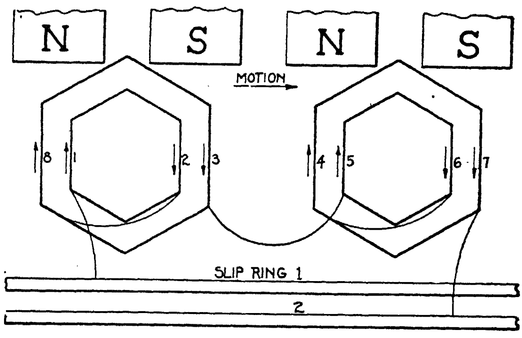

Fig. 177. Developed Diagram of Single-Phase Half-Coil Winding for Four-Pole Machine

A whole-coil winding is one in which there is a whole-coil roup per phase per pole. A single-phase, whole-coil winding for a

four-pole machine is shown in Fig. 178, and a development of the winding is given in Fig. 179. Each of the coil groups in Figs. 178 and 179 is composed of two coils in series, one inside the other.

(4) **With respect to number of slots**

(a) Concentrated or unicoil windings
(b) Distributed or multicoil windings { Partially distributed / Fully distributed

A concentrated winding is one in which all the inductors per phase per pole are grouped in a single slot per pole.

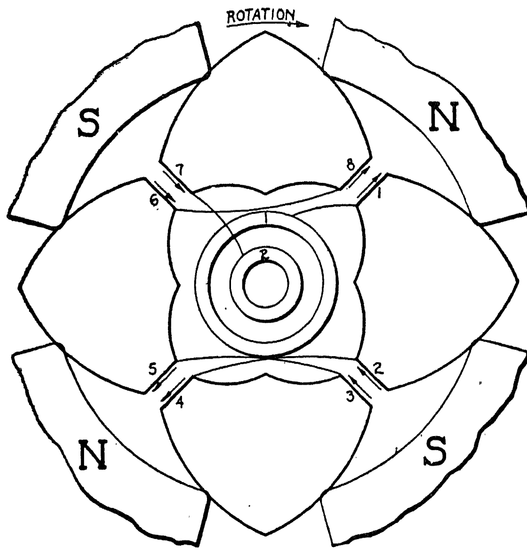

Fig. 178. Radial Diagram of Single-Phase Whole-Coil Winding for Four-Pole Machine

A distributed or multi-coil winding is one in which the inductors per phase per pole are distributed in several slots per pole. Partially distributed single-phase armature windings, placed in two slots per pole, are shown in Figs. 176, 177, 178, and 179. A fully distributed armature winding which is distributed in six slots per phase per pole is shown in Fig. 180, and a developed

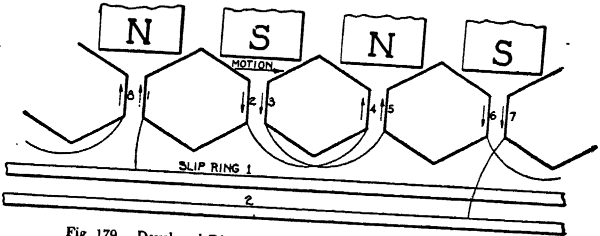

Fig. 179. Developed Diagram of Single-Phase Whole-Coil Winding for Four-Pole Machine

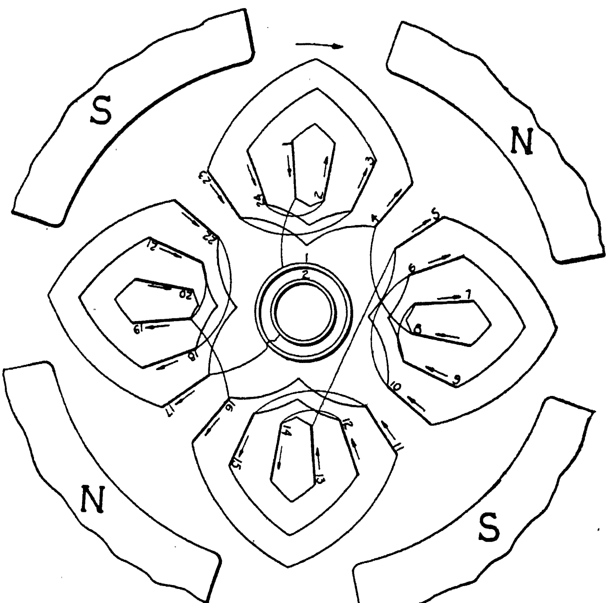

Fig. 180. Radial Diagram of Fully Distributed Single-Phase Armature Winding for Four-Pole Machine

diagram of the winding is given in Fig. 181. In a winding of this kind the total e.m.f. per half-coil group is made up of three e.m.f.'s equally spaced from each other by 30 electrical degrees. Each of these e.m.f.'s will have the same numerical value provided each slot contains the same number of inductors.

(4) With respect to form of inductors

(a) Wire winding
(b) Strap winding
(c) Bar winding

In the construction of alternating-current armatures either wire, strap, or bar inductors may be used, depending upon which is best suited for the particular requirements. The size and shape

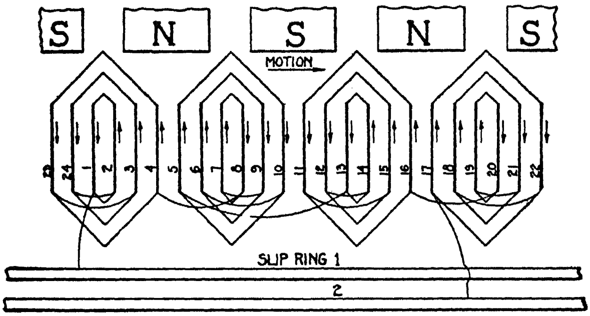

Fig. 181 Developed Diagram of Fully Distributed Single-Phase Armature Winding for Four-Pole Machine

of the inductor is governed by the current the inductor must carry and the space in which the inductor is to be placed. Thus in a high-voltage machine small well-insulated wire will be required, while in a low-voltage machine large inductors not so well insulated will be required. In order that the coils may be flexible several small wires in parallel are often used instead of a single large wire.

(6) With respect to number of coils per phase per pole

(a) Single-slot winding
(b) Multi-slot winding

A single-slot winding is one in which all the inductors per phase per pole are placed in a single slot, while a multi-slot winding is one in which the inductors per phase per pole are distributed

TABLE VIII

Effectiveness of Single-Phase Armature Winding Having Six Slots per Phase per Pole

Slots in Use	Voltage Across Coils	Distribution Factor	Quantity of Copper to Produce Same Voltage
1	1.00	1.00	1.00
2	1.93	0.97	1.03
3	2.73	0.91	1.10
4	3.34	0.84	1.19
5	3 72	0.74	1.35
6	3.86	0.64	1.56

in several slots. In the majority of cases only two-thirds of the total number of slots, assuming they are all equally spaced, are used for a single-phase armature winding. The reason for this is that more copper is required for a given generated pressure as the distribution of the winding is increased. If much less than two-thirds of the surface of the armature be wound, it is often quite difficult to provide a sine wave of pressure. Table VIII shows what might be called the effectiveness of the winding for an armature having six slots per pole.

(7) **With respect to kind of current delivered**

(a) Single-phase winding
(b) Two-phase winding
(c) Three-phase winding

A single-phase winding is one in which there is but a single e.m.f. induced in the winding.

A two-phase winding is one in which there are two e.m.f.'s induced in the winding and these e.m.f.'s are displaced in phase with respect to each other by 90 electrical degrees.

A three-phase winding is one in which there are three e.m.f.'s induced in the winding and these e.m.f.'s are displaced in phase with respect to each other by 120 electrical degrees.

(8) **With respect to shape of coil ends**

(a) Single range
(b) Two range, etc.

A single-range armature winding is one in which all the coil ends are of the same shape.

A two-phase, two-range armature winding is shown in Fig. 182 and it will be observed that the coils composing phase A have

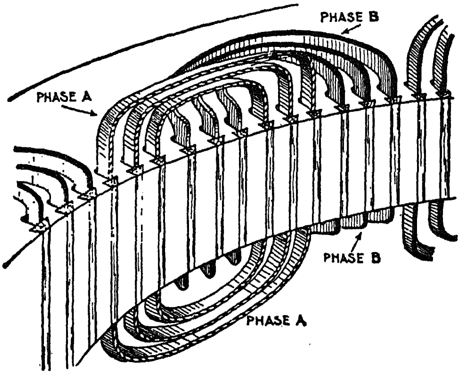

Fig. 182. Diagram Showing End-Connections of Two-Phase, Two-Range Armature Winding

their ends coming straight out from the slots, while the coils composing phase B have their ends bent down. Another two-phase, two-range winding is shown in Fig. 183.

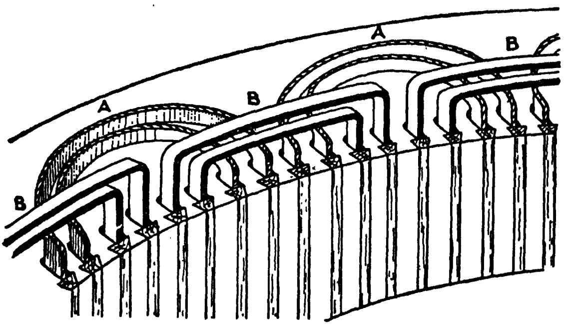

Fig. 183. Diagram Showing End-Connections of Two-Phase, Two-Range Armature Winding

Two three-phase, three-range windings are shown in Figs. 184 and 185. The arrangement shown in Fig. 185 will permit the armature being separated without unwinding any of the coils.

(9) **With respect to arrangement of coil sides in slots**

(a) Single-layer winding
(b) Double-layer winding

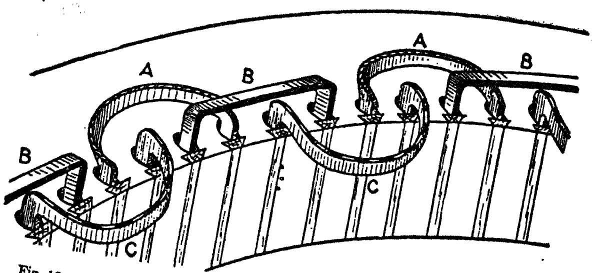

Fig. 184. Diagram Showing End-Connections of Three-Phase, Three-Range Armature Winding

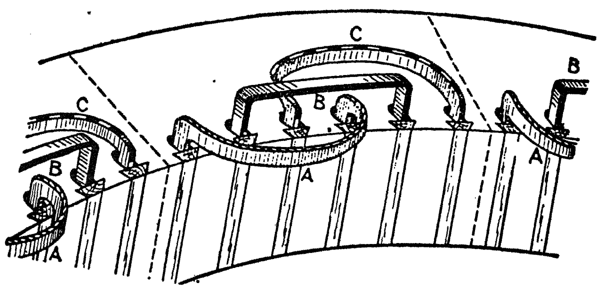

Fig. 185. Diagram Showing End-Connections of Three-Phase, Three-Range Armature Winding

A single-layer winding is one in which there is only a single layer of coil sides in each of the slots. In the whole-coil windings there are two half coils in each slot, but these two half coils are side by side.

A double-layer winding is one in which there are two coil sides placed one above the other in the slots. The form of a single coil in a two-layer winding is shown in Fig. 186, and a possible cross-section of a slot of a two-layer winding is shown in Fig. 187.

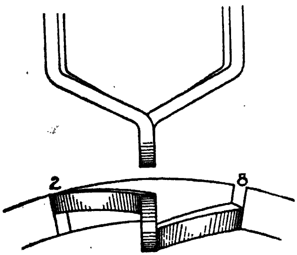

Fig. 186. Form of Single Coil for Two-Layer Winding

(10) With respect to number of circuits through winding per phase

(a) Single-circuit winding
(b) Two-circuit winding, etc.

A single-circuit winding is one in which all the inductors per phase are in series and there is only one path for the current from one collecting ring to the other for each particular phase.

A two-circuit armature winding is one in which the inductors per phase are connected in such a manner that there are two paths for the current from one collecting ring to the other for each particular phase, etc. For a constant number of inductors, the number of inductors in series in each path for a two-circuit winding is just one-half of what it is for a single-circuit winding, but the current capacity of the two-circuit winding is twice that of the single-circuit winding. A single-circuit, three-phase, Y-connected winding is shown in Fig. 188, and the same winding reconnected as a two-circuit winding is shown in Fig. 189.

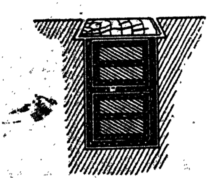

Fig. 187 Typical Cross-Section of Slot for Two-Layer Winding

A single-circuit, three-phase Δ-connected winding is shown in Fig. 190, and the same winding reconnected as a two-circuit winding is shown in Fig. 191.

A single- and a two-circuit, two-phase armature winding are shown in Figs. 192 and 193 respectively.

Four different types of connections for a three-phase, double-layer armature winding are shown in Figs. 194, 195, 196, and 197.

(II) **Miscellaneous windings**

(a) Chain windings	(d) Mummified windings
(b) Skew-coil windings	(e) Shuttle windings
(c) Fed-in windings	(f) Creeping windings, etc.

A chain winding is one in which the different coils link one another as the links in a chain, which accounts for the name. A chain winding is shown in Fig. 198.

A skew-coil is one in which the ends of the coils are all made the same shape, which results in only a single form being required for the coils.

A fed-in winding is one in which the inductors are fed into the slots from the top, or ends, the slot being provided with a lining of horn fiber or other suitable insulating material, which is usually folded over and secured by means of a wedge, or by some other suitable means.

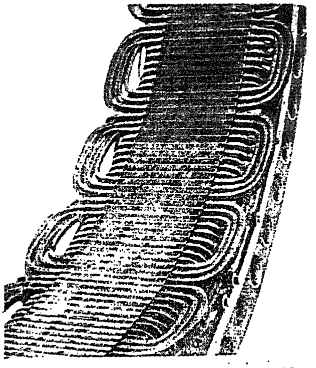

Fig. 198. Three-Phase Chain Winding, Having Three Half Coils per Phase per Pole
Courtesy of General Electric Company, Schenectady, New York

A mummified winding is one composed of coils which were saturated and baked before they were placed on the armature.

A shuttle winding is one consisting of a single coil having a large number of turns wound in two slots on the armature 180 electrical degrees apart. This type of winding is used a great deal in the construction of magnetos.

A creeping winding is one composed of coils having a fractional pitch and the coils composing each phase are so arranged as to gain or lose one or more complete pole pitches as you trace around the armature.

Principal Parts of Alternating-Current Machine. A sectional view of an alternating-current motor is shown in Fig. 199, and the names of the principal parts are indicated below the figure.

Examples of Alternating-Current Windings. Bars for lap and for wave windings are shown in Fig. 200. The upper formed

bar is for a lap winding and the lower formed bar is for a wave winding. A number of armature coils are shown in Fig. 201

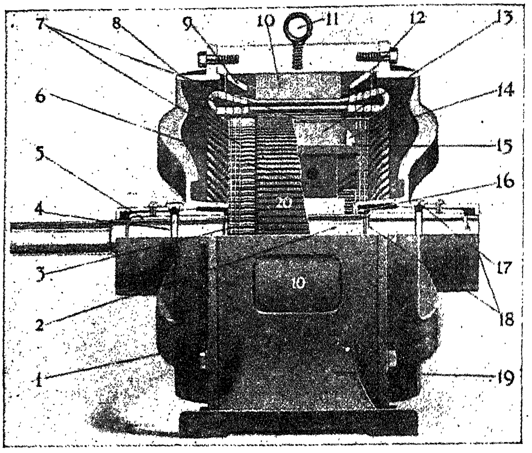

Fig. 199. Sectional View Showing Principal Parts of Alternating-Current Motor
Courtesy of Reliance Electric and Engineering Company, Cleveland, Ohio

1. End Bracket; 2. Shaft; 3. Rotor Short-Circuiting Rings; 4. Oil Rings; 5. Self-Aligning Bearing Bushing; 6. Spider; 7. Rotor Bars; 8. Stator Coils; 9. Stator Lamination End-Plate; 10. Stator Laminations; 11. Eyebolts; 12. Stator Locking Key; 13. Rotor Laminations; 14. Rotor Lamination End-Plate; 15. Rotor Locking Key; 16. Dust Cap; 17. Oil-Well Cover; 18. Oil Throws; 19. Stator Frame; 20. Rotor

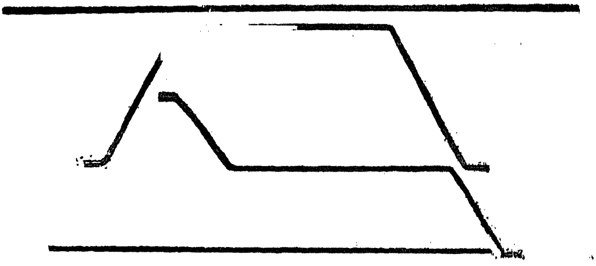

Fig. 200. Bars for Lap and Wave Windings
Courtesy of General Electric Company, Schenectady, New York

for an 11,000-volt generator. The different steps in the insulation of the coils are shown from the bare coil to the completed coil.

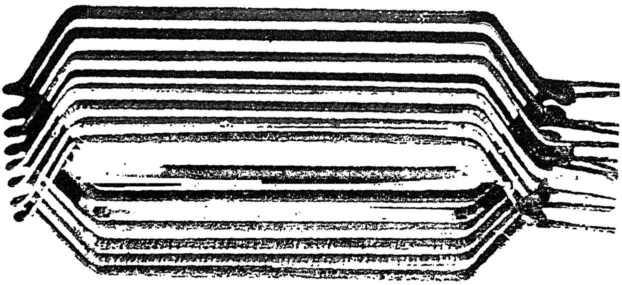

Fig. 201. Armature Coils in Different Steps in Process of Being Insulated
Courtesy of General Electric Company, Schenectady, New York

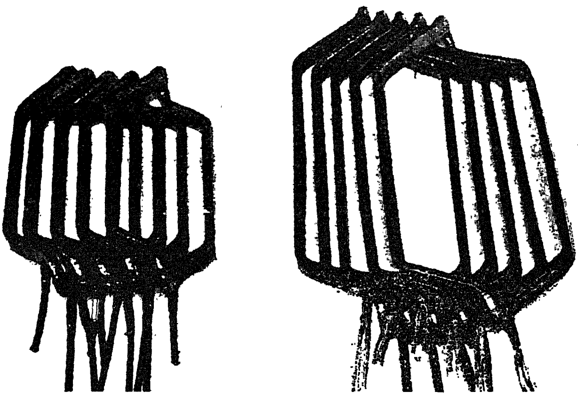

Fig. 202. Completed Armature Coils
Courtesy of Allis-Chalmers Manufacturing Company, Milwaukee, Wisconsin

A number of completed armature coils are shown in Fig. 202. These coils have a uniform insulation on the slot portion of the coils and on the ends. Oftentimes the slot part of the coil is better insulated than the ends.

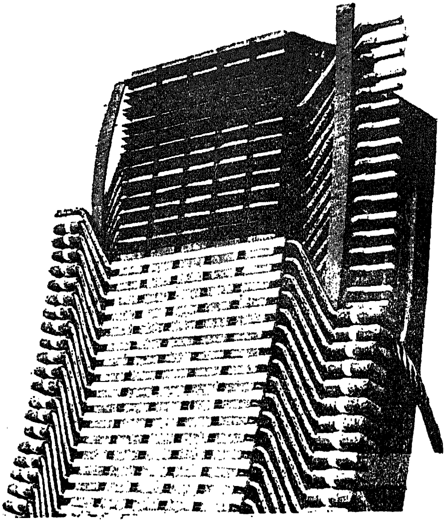

Fig. 203. Bar Winding in Process of Construction
Courtesy of General Electric Company, Schenectady, New York

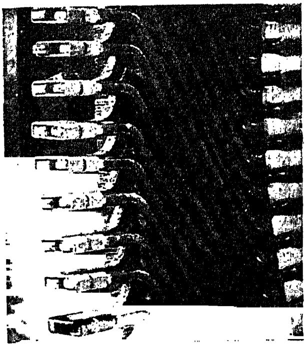

Fig. 204. Method of Connecting Ends of Bars in Bar Winding
Courtesy of General Electric Company Schenectady, New York

A bar winding is shown in Fig. 203, and the method of making the end-connections is shown in Fig. 204. This is a wave winding as the ends of the bars are bent in opposite directions at the front and back of the armature.

The stator for a 600-volt General Electric generator is shown in Fig. 205, and the stator for a 2300-volt General Electric

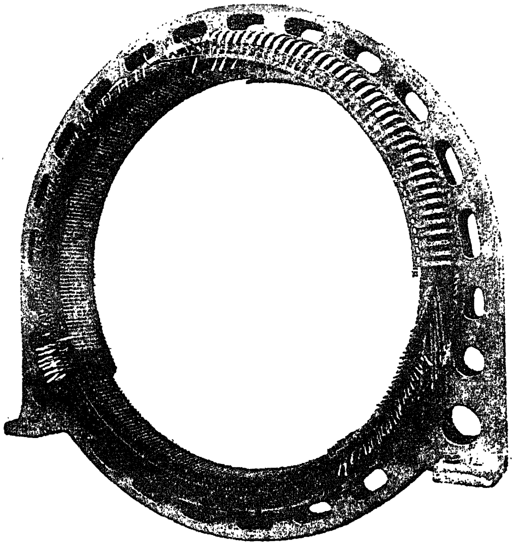

Fig. 205. Partially Completed Stator for General Electric 600-Volt Generator

synchronous motor is shown in Fig. 206. Both these windings are of the double-layer type.

A double stator winding is shown in Fig. 207, as used by the Allis-Chalmers Company, in a 2200-volt, 25-cycle, 3-phase, 2-speed induction motor.

The stator for a 1500-horsepower, 6600-volt, 3-phase, wound-rotor, induction motor, as manufactured by the Allis-Chalmers Company, is shown in Fig. 208.

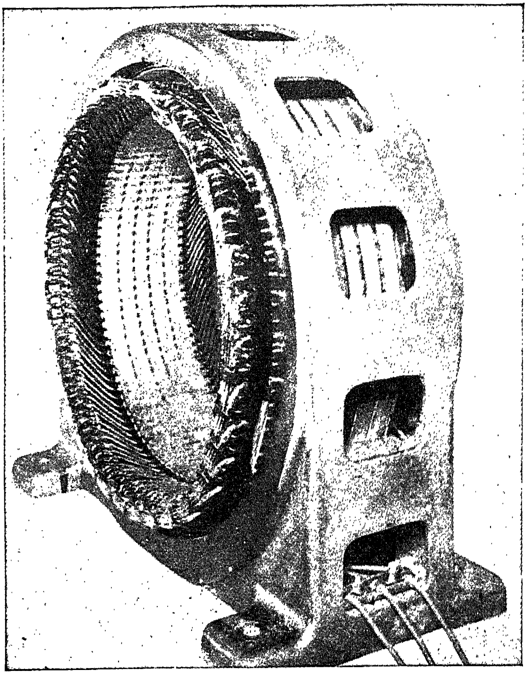

Fig 206 Completed Stator for 2300-Volt Synchronous Motor
Courtesy of General Electric Company, Schenectady, New York

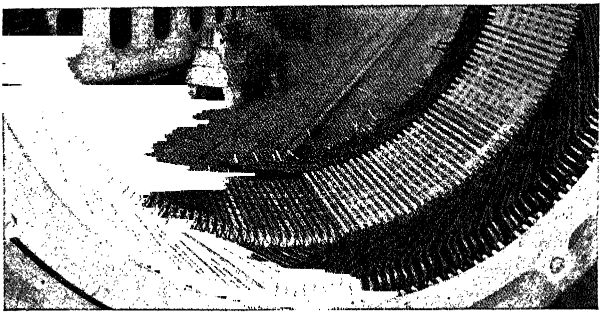

Fig. 207. Double-Stator Winding for 600-Horsepower, 2200-Volt, 3-Phase, 25-Cycle, Two-Speed, Allis-Chalmers Induction Motor

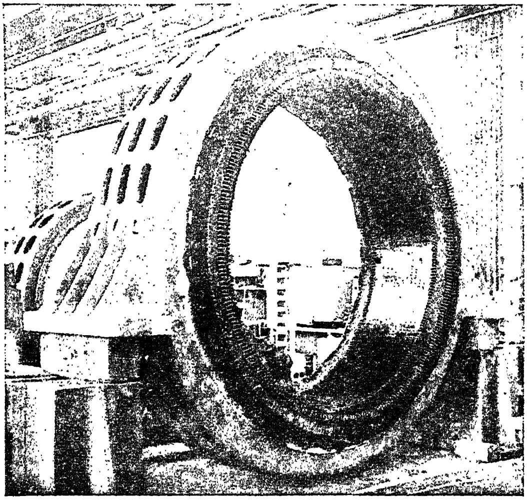

Fig. 208. Stator for 1500-Horsepower, 150 R.P.M., 6600-Volt, Wound-Rotor Induction Motor
Courtesy of Allis-Chalmers Manufacturing Company, Milwaukee, Wisconsin

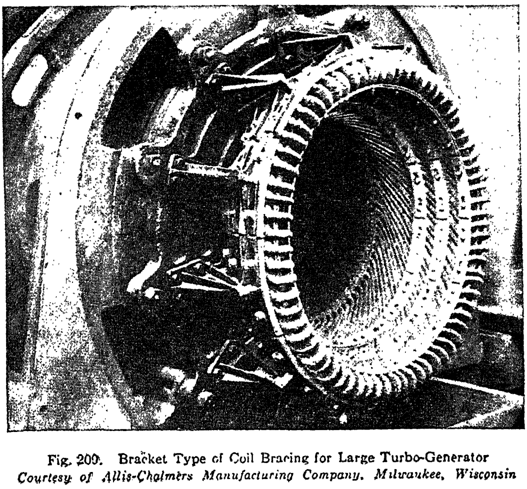

Fig. 209. Bracket Type of Coil Bracing for Large Turbo-Generator
Courtesy of Allis-Chalmers Manufacturing Company, Milwaukee, Wisconsin

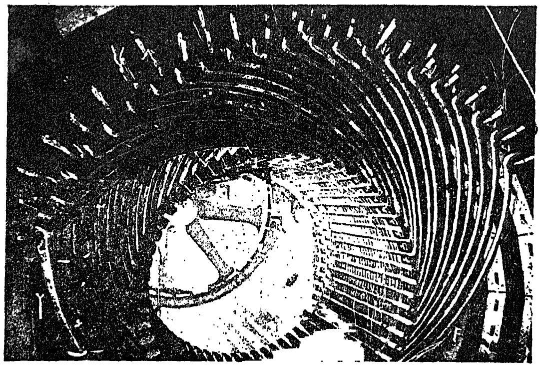

Fig. 210. Method of Bracing Coils for Large Turbo-Generator
Courtesy of Allis-Chalmers Maunfacturing Company, Milwaukee, Wisconsin

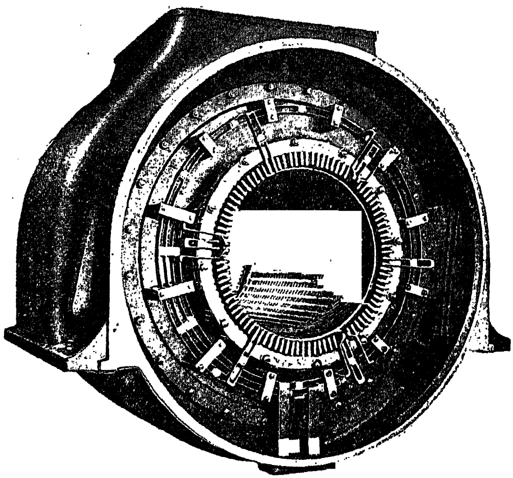

Fig. 211. End-Connections for Large Turbo-Generator
Courtesy of Allis-Chalmers Manufacturing Company, Milwaukee, Wisconsin

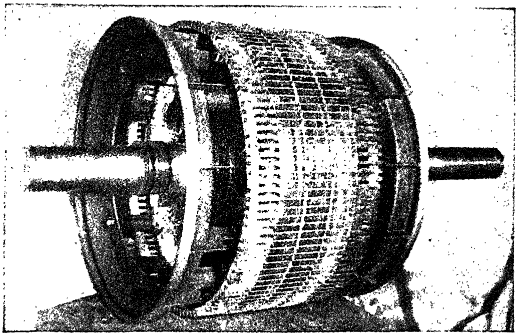

Fig. 212. Rotor for Large Squirrel-Cage Induction Motor
Courtesy of Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pennsylvania

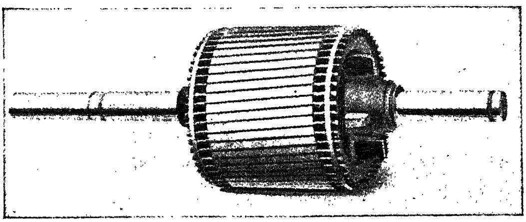

Fig. 213. Rotor for Small Squirrel-Cage Induction Motor
Courtesy of Reliance Electric and Engineering Company, Cleveland, Ohio

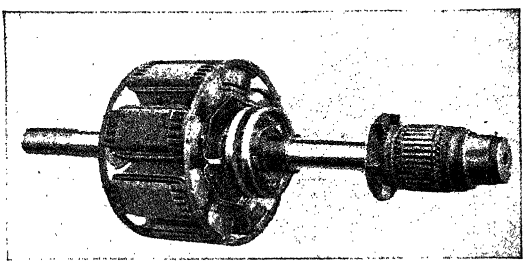

Fig. 214. Special Squirrel-Cage Winding on Rotor of Synchronous Motor
Courtesy of Allis-Chalmers Manufacturing Company, Milwaukee, Wisconsin

The method of bracing the coils on two large turbo generators is shown in Figs. 209 and 210. The end-connections for a large turbo generator are shown in Fig. 211.

The rotor for a Westinghouse squirrel-cage induction motor is shown in Fig. 212. The winding consists of a number of bars which have their ends electrically connected to two metal rings, one at each end of the rotor. The bars are usually insulated from the iron core, but not always.

The rotor for a small induction motor is shown in Fig. 213. The slots are given a slight twist, as shown in the figure. This assists in the operation of the machine, as the inductors do not move into and out of the magnetic field as suddenly as they would otherwise.

A special squirrel-cage winding is shown in Fig. 214. Inductors are embedded in the surface of the pole shoes, and their ends are connected to metal rings at opposite ends of the rotor. Such windings are used on synchronous motors in starting them as they may then be started as induction motors.

RECONNECTING INDUCTION-MOTOR ARMATURE WINDINGS

Possible Changes. Occasionally it is necessary to make changes in the motor equipment of a plant, due to changes in the operating voltage, frequency, or number of phases of the circuit supplying energy. In such cases it is frequently possible to use the old motors by making certain changes in their connections or construction, and in some cases no changes in the internal connections of the motor may be required. Considered in the order of their desirability, the possibilities in such cases are as follows:

(1) Motor operated under new conditions without change in internal connections
(2) Reconnection of the old windings to meet the changed conditions
(3) Supplying a complete new set of coils
(4) Supplying new laminations and also new coils

Fundamental Ideas of the Electric Motor. An electric motor is a means of transforming electrical energy into mechanical energy in the form of a rotative force. This rotative force, or

torque, is produced by the force exerted on a current flowing in a conductor which is located in a magnetic field. Hence, it follows at once that the capacity of a motor for producing torque is limited by the capacity of the electrical circuit to carry current and also by the capacity of the magnetic circuit to carry magnetic lines of force, or flux. The heating of a motor depends upon both the current density in the copper and the flux density in the iron. These densities are usually fixed by the designing engineer so that the temperature of the motor will not become excessive under its rated or guaranteed load. It follows, that if changes are to be made in the voltage, frequency, phase, or speed of the motor, the number of turns of copper must be changed or a reconnection made so as to preserve approximately the same current density in the copper and the same flux density in the iron that existed before the changes were made. The above statement is true over a very wide range of conditions, and would be true universally were it not for the fact that the ventilation of a machine is poorer at low speed than at high, and hence the same heat losses cannot be dissipated. For this reason it is generally true that the capacity of a motor may increase directly as the speed when the speed is being increased, but may decrease somewhat faster than the speed when the speed is being decreased. As an example, a 50-horsepower motor at 600 r.p.m. may be made to develop 100 horsepower at 1200 r.p.m., assuming that the mechanical design would stand the increased speed, but conversely, a motor originally designed for 100 horsepower at 1200 r.p.m. when reduced to 600 r.p.m. might not develop more than 40 horsepower on account of reduced ventilation.

It is the object of the following sections to describe briefly what questions must be considered to determine whether the characteristics of the motor may be changed in the manner desired; second, what the effect will be on the windings of the motor with respect to the number of turns in the coils and the mechanical form of the coils; and third, by what simple mechanical means, such as reconnection, if possible, the desired change may be accomplished.

Torque and Horsepower. In considering the operation of any motor it is essential that you get a clear conception of the

distinction between torque and horsepower. It is the primary function of a motor to produce torque, or rotative force, and it is incidental that when this same torque is allowed to rotate at one speed or another a different horsepower is produced. For this reason it is not correct in speaking of a motor to say "It required 30 horsepower to start the load," because, when starting, the motor was at a standstill—that is, there was no rotation, and hence it was developing no horsepower. The motor, however, was taking current and developing torque, and the correct expression would be: "The current taken at the start was equivalent to the current when developing 30 horsepower after the motor is up to speed."

Motor Acting as Generator. In addition to the above it is essential that you always bear in mind that a motor is acting as a generator, aside from and in addition to its motor action. To think of this action it is necessary to forget for the time the torque action produced by the conductor in the magnetic field and to think of the same conductor moving across the magnetic field and having an e.m.f. induced in it. The cycle of operations in a motor are briefly as follows: first, the magnetic field is produced; second, current flows in the conductors producing torque; and third, the torque moves the conductors across the magnetic field and an e.m.f. is induced in them. This e.m.f. is called the counter-e.m.f., as its direction is practically opposite to the applied voltage, and it is practically equal to the applied voltage except for the small loss in the motor. It necessarily follows, that designing a motor is primarily designing a generator for the line voltage. With this conception of the operation of the motor and the fundamental formula for the e.m.f., it is a simple matter to write expressions showing how the turns in a motor should vary with different line voltages and for different speeds, etc.

The above relations are sufficiently simple to be borne in mind at all times and they offer the readiest first-hand answer to the probable results of operating a motor under changed conditions.

Classification of Probable Changes in Connections of Motor Winding. Before taking up some of the more common changes in detail it will be best to make a classification of the changes which may be made.

Some changes are such that the operation of the motor remains practically the same as before reconnection. Such changes, for example, are represented by connecting the polar groups of a winding in series for 440 volts and in parallel for 220 volts. These changes will be referred to as Class A changes.

A second class of changes leaves the performance of the motor in some respects unchanged and alters it in others. For example, a motor may be operated in star on 440 volts, and in delta on 220 volts. In such a case there is a little change in the efficiency or power factor, but the starting and maximum torques are only about 75 per cent of their original value. The advisability of such a change will depend upon the nature of the work this motor is doing. If the altered values of the torques are sufficient to start and carry the load, there is no objection to operating the motor when reconnected, as the motor will not run any warmer. Such changes will be referred to as Class B changes.

A third class of changes leaves the performance of the motor practically unchanged so far as the torque is concerned, but so alters its performance as to heating, or efficiency, or power-factor, or insulation, that it is undesirable to leave the motor operating indefinitely in such a condition. For example, such changes are represented by taking a three-phase motor and reconnecting the coils as they stand for two-phase. A change of this kind is equivalent to operating a three-phase motor at approximately 125 per cent normal voltage. In addition, the phase insulation between the polar groups will not be correct. There will be a large increase in the iron and heating losses and the power factor will be decreased. Such changes should be considered as emergency changes and the permanent changes made as soon as possible. For convenience such changes will be referred to as Class C changes.

Shop and Working Diagrams. *Conventional Method.* It is quite difficult and tedious to represent winding diagrams as shown in Figs. 194, 195, 196, and 197, and for this reason a conventional method of giving the same information has been adopted. This method is shown in Fig. 215. In this scheme the various pole groups are represented by short arcs. The arrows on the arcs are shown simply to indicate a method of checking up to ensure the

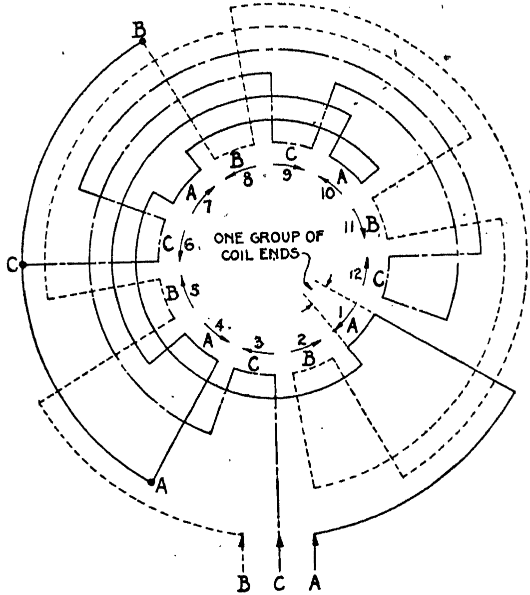

Fig. 215. Conventional Diagram of Armature Winding

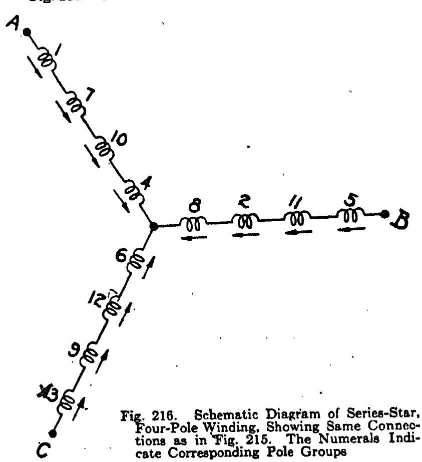

Fig. 216. Schematic Diagram of Series-Star, Four-Pole Winding, Showing Same Connections as in Fig. 215. The Numerals Indicate Corresponding Pole Groups

proper phase relations. There is considerable danger of getting a 60-degree relation between the phases in a three-phase winding instead of 120 degrees; or, the wrong end of one of the phases may be connected to the star point. Arrows are put on all the pole-phase groups, and when all three phases are traced through, the winding is correct if the arrows on consecutive groups run

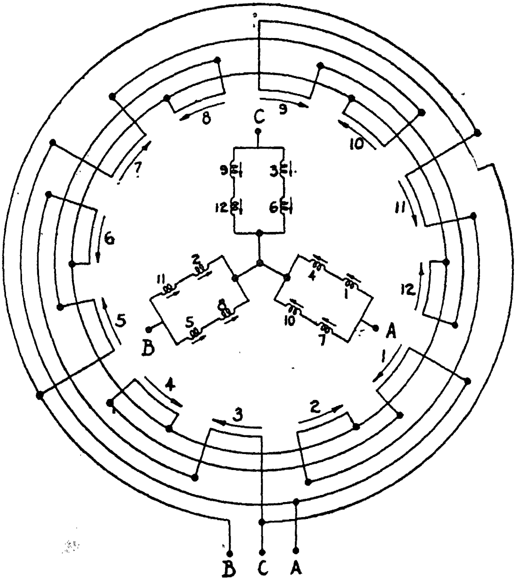

Fig. 217. Conventional Three-Phase, Four-Pole, Parallel-Star Diagram, and Schematic Equivalent

alternately clockwise and counterclockwise. There is but one exception to the correctness of the check as shown in Figs. 215 and 216, and the succeeding figures where the current is assumed as flowing toward the star in all three phases and the arrows alternate in direction. This one exception to the rule is the case where the winding forms consequent poles or passes through all the phase-pole groups in a north direction instead of alternately

north and south. Such connections are rarely used, and then usually on special motors wound for multi-speeds.

Parallel Star Diagram. A combined conventional and schematic representation of a so-called "parallel star" diagram, where the two halves of each phase are in parallel, is shown in Fig. 217. If a machine be connected originally as shown in Fig. 215 and its voltage rating be 440 volts, it could readily be connected

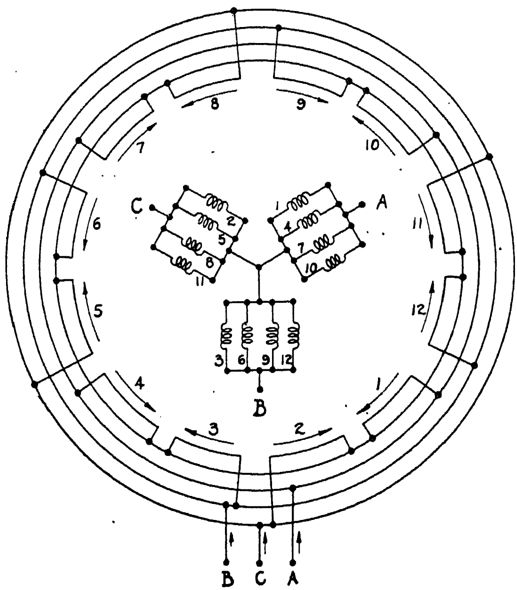

Fig. 218. Conventional Three-Phase, Four-Pole, Four-Parallel, Star Diagram, and Schematic Equivalent

as shown in Fig. 217 and it would operate on a 220-volt circuit satisfactorily. The performance would be the same in all respects except that it would draw from the 220-volt line twice as many amperes for a given load as it originally drew from the 440-volt line.

If the machine had four poles, or a multiple of four poles, it could still be paralleled again, or connected 4-parallel star, as

shown in Fig. 218, and operated on a 110-volt circuit, and would still have the same performance but a correspondingly increased current at the same load.

Delta Diagram. Fig. 219 represents a so-called delta, or mesh, connection. If a machine connected as in Fig. 215 for 440 volts be reconnected as in Fig. 219, it will be suitable for opera-

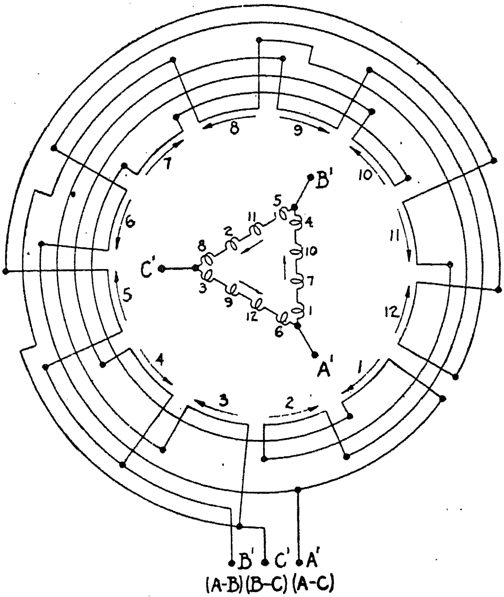

Fig. 219. Conventional Three-Phase, Four-Pole, Series-Delta Diagram, and Schematic Equivalent

tion on a circuit having a voltage of 440÷1.73 or 254 volts. Reconnections or conversions of this kind are shown in Table IX, where the preceding problem may be worked out by selecting 3-phase series star in the horizontal column—first line—and reading across to the vertical column headed "3-Ph. Series Delta" where the figure 58 appears.

TABLE IX

Comparison of Motor Voltages with Various Connections

	3-Ph. Series Star	2-Ph. 2-Par. Star	3-Ph. 3-Par. Star	3-Ph. 4-Par. Star	3-Ph. 5-Par. Star	3-Ph. Series Delta	3-Ph. 2-Par. Delta	3-Ph. 3-Par. Delta	3-Ph. 4-Par. Delta	3-Ph. 5-Par. Delta	2-Ph. Series	2-Ph. 2-Par	2-Ph. 3-Par.	2-Ph. 4-Par.	2-Ph 5-Par.
3-Ph. Series Star........	100	50	33	25	20	58	29	19	15	12	81	41	27	20	16
3-Ph. 2-Par. Star........	200	100	67	50	40	116	58	38	29	23	162	81	54	40	32
3-Ph. 3-Par. Star........	300	150	100	75	60	174	87	57	44	35	243	122	81	60	48
3-Ph. 4-Par. Star........	400	200	133	100	80	232	116	76	58	46	324	163	108	80	64
3-Ph. 5-Par. Star........	500	250	165	125	100	290	145	95	73	58	405	203	135	100	80
3-Ph. Series Delta......	173	86	58	43	35	100	50	33	25	20	140	70	47	35	28
3-Ph. 2-Par. Delta......	346	172	116	86	70	200	100	66	50	40	280	140	94	70	56
3-Ph. 3-Par. Delta......	519	258	174	129	105	300	150	100	75	60	420	210	141	105	84
3-Ph. 4-Par. Delta......	692	344	232	172	140	400	200	133	100	80	560	280	188	140	112
3-Ph. 5-Par. Delta......	865	430	290	215	175	500	250	165	125	100	700	350	235	175	140
2-Ph. Series............	125	63	42	31	25	73	37	24	18	15	100	50	33	25	20
2-Ph. 2-Parallel........	250	125	84	63	50	146	73	49	37	29	200	100	67	50	40
2-Ph. 3-Parallel........	375	188	125	94	75	219	110	73	55	44	300	150	100	75	60
2-Ph. 4-Parallel........	500	250	167	125	100	292	146	97	73	58	400	200	133	100	80
2-Ph. 5-Parallel........	625	313	208	156	125	365	183	122	91	73	500	250	167	125	100

NOTE—If a motor connected originally as shown in any horizontal column had a normal voltage of 100 its voltage when reconnected as indicated in any vertical column is shown at the intersection of the two columns.

This means that if 100 volts was normal on the series-star connection and a change is made to series delta, the corresponding voltage is 58 volts. If the series-star voltage was 440, then the series delta voltage would be 4.4 times 58, or 254 volts. Single-parallel and four-parallel delta connections are shown in Figs. 220 and 221 respectively.

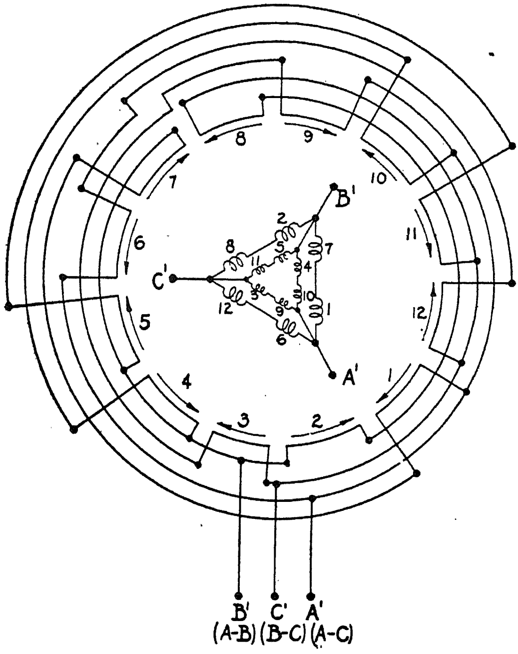

Fig. 220. Conventional Three-Phase, Four-Pole, Parallel-Delta Diagram, and Schematic Equivalent

Two-Phase Development. A development of a two-phase winding is shown in Fig. 222. An inspection of the coils represented in heavier lines indicates what is meant by phase-insulated coils or "phase coils." In changing from a two- to a three-phase connection, or vice versa, the position of these coils will change;

hence the phase insulation is not sufficient in the case of the reconnected winding.

The conventional and schematic equivalent of Fig. 222 is given in Fig. 223. The arrows shown in the three-phase diagrams are omitted here, for the reason that the two phases are not interconnected, and the only effect of reversing one phase is to reverse

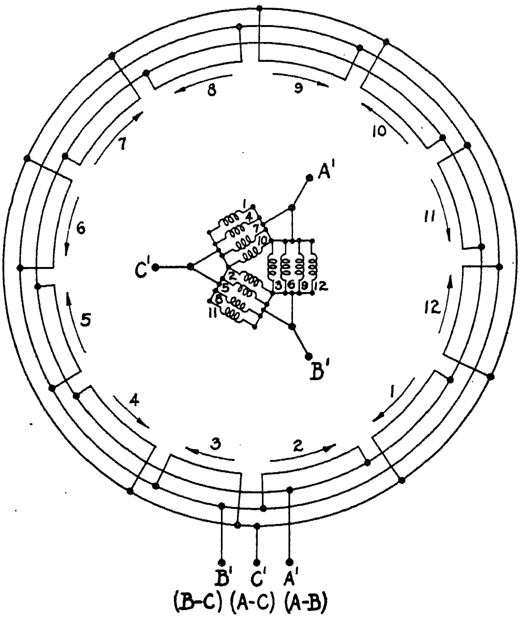

Fig. 221. Conventional Three-Phase, Four-Pole, Four-Parallel, Delta Diagram, and Schematic Equivalent

the direction of rotation of the motor. Either phase can readily be reversed by reversing the two leads of that particular phase at the motor terminals. Single- and four-parallel, two-phase connections are given in Figs. 224 and 225, respectively. Where the number of poles is a multiple of three, as 6, 12, 18, etc., there is a possible 3-parallel connection; where the number of poles is a

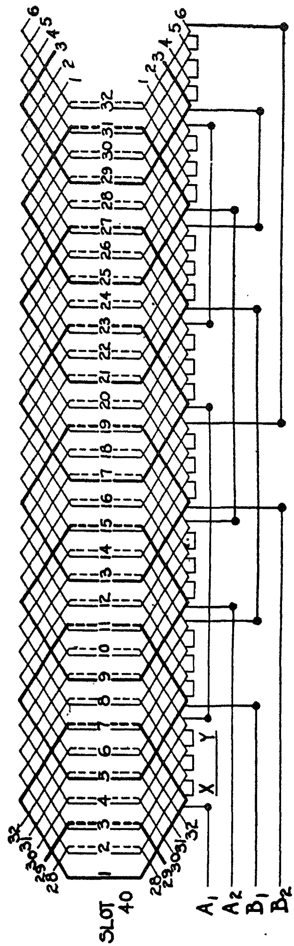

Fig. 222. Developed Diagram of Four-Pole, Two-Phase, Series-Connected Armature Winding, Coils from X to Y Form One-Pole Phase Group

TABLE X

Comparative Performances

Comparison of a two-phase motor reconnected for operation on three-phase by a T connection and the performance of the same motor when supplied with new three-phase coils and connected as a normal three-phase motor.

	Normal Two-Phase Winding	Three-Phase "Tee" Connection	Normal Three-Phase Winding
Full-load Efficiency	88	86.9	88.5
Full-load Power Factor	89	84.8	90
Starting Torque	1.75	1.20	1.94
Maximum Torque	3.3	3.17	3.3
Degrees C. Rise at Full Load for			
Stator Copper	22.5	32	21
Stator Iron	20	32.5	19
Rotor Copper	22	30	22

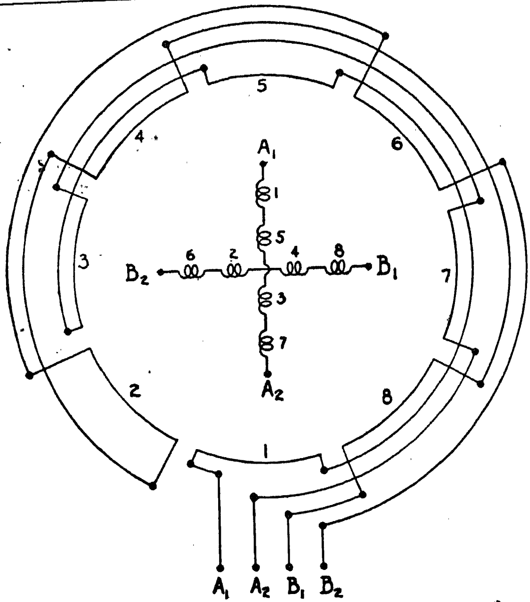

Fig. 223. Conventional Two-Phase, Four-Pole, Series Diagram, and Schematic Equivalent

multiple of five, such as 10, 20, etc., there is a possible 5-parallel connection.

Three-Phase Development. A possible three-phase connection which may be made from a two-phase winding by a method similar to the Scott transformer connection is shown in Fig. 226. The effect of this connection is shown in Table X. It should be used only as a temporary arrangement.

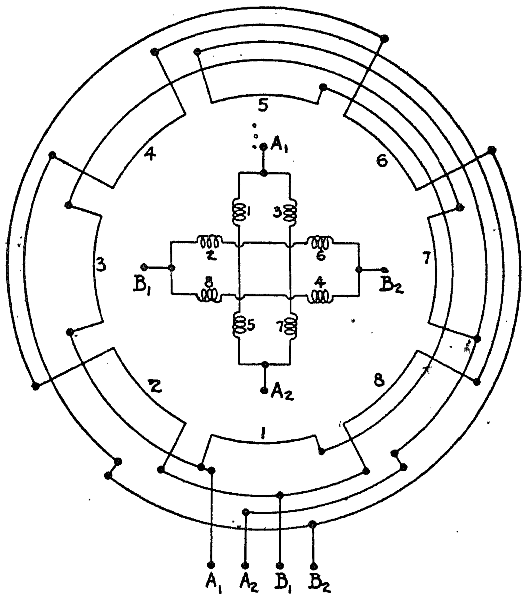

Fig. 224. Conventional Two-Phase, Four-Pole, Single-Parallel Diagram, and Schematic Equivalent

Least Common Multiple Connection. An interesting connection is shown in Fig. 227, and it is called the "least common multiple" connection. In this winding the number of slots in the machine is not a multiple of the phases times the poles, and as a result there are more coils in some groups than in others, which introduces a slight displacement at these points. The coils are

however, displaced around the machine, so as to produce a perfectly balanced voltage at the terminals of the machine. This type of connection enables the manufacturers to make use of one stamping for the greatest possible number of combinations of phases and poles.

Three-Phase Motor Diagram. Figs. 228 and 230 show the usual connections for a three-phase motor which can be connected

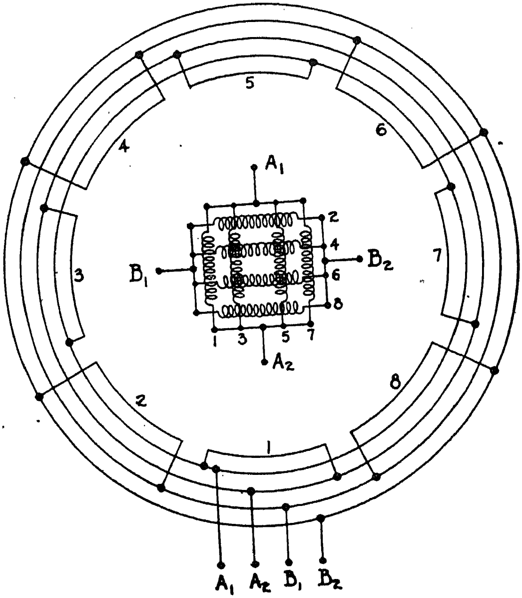

Fig. 225. Conventional Two-Phase, Four-Pole, Four-Parallel Diagram, and Schematic Equivalent

to give two sets of poles or two speeds in the rate of two to one. In Fig. 228 the high speed is parallel star and the low speed series star. The location of the poles for the two-speed connections given in Fig. 228 is given in Fig. 229, which is an explanatory diagram showing schematically how the two sets of poles are produced. In Fig. 230 the high speed is parallel star and the low

speed series delta. The connections shown in Fig. 228 give better results where a constant torque is required, and it gives twice the horsepower on the high speed that it develops on the low speed. The connections shown in Fig. 230 give somewhat better results where a constant horsepower is desired at both the low and high speeds, as in the case with most machine-tool applications.

Two-Phase, Two-Speed Diagram. A similar diagram for a two-phase, two-speed connection where the winding is in parallel

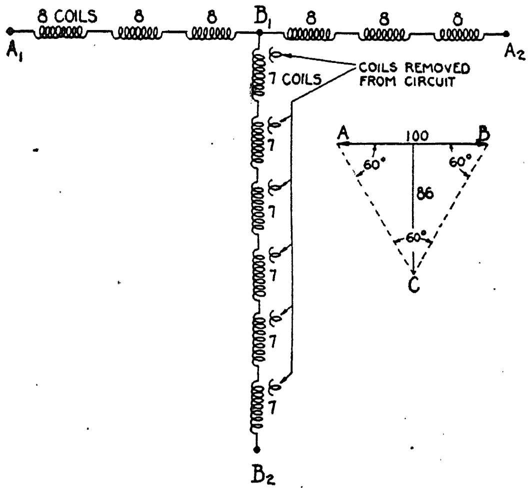

Fig. 226. Diagram of Scott or T Connections

on the high speed and in series on the low speed is shown in Fig. 231. A very interesting point in connection with this winding is that it overcomes one of the disadvantages of the corresponding three-phase windings shown in Figs. 228 and 230, by putting half of the winding in one phase for the low-speed connection and half in the other phase for the high-speed connection. This is of particular advantage as the distribution factor remains the same for both speeds, as in a normal two-phase machine. In the three-phase windings shown in Figs. 228 and 230, the distribution factor is only 86.1 per cent as good on the low-speed

connection as on the high-speed connection. This results in a loss in horsepower on the low-speed connection of approximately 30 per cent.

In all the previous diagrams the phase pole group has been treated as a single unit. That is, if there were four coils per phase per pole these four coils were connected in series in a group and

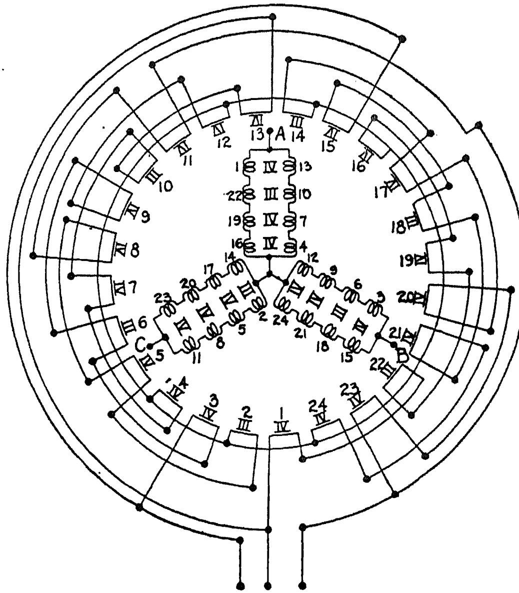

Fig. 227. Conventional Three-Phase, Eight-Pole, Parallel-Star Diagram and Schematic Equivalent. (With Balanced Phases on Machine Having 90 Slots. The Number of Coils in Each Pole Phase Is Shown by Roman Numerals.)

handled as a unit. A type of connection which breaks up these groups is shown in Fig. 232. This type of connection is not very satisfactory and should not be resorted to except in an extreme emergency.

Possible Reconnections. The following changes are those which are most frequently encountered in ordinary commercial

work, and the manner in which they can best be taken care of will be discussed briefly in the following paragraphs:

Changes in voltage and phase of the supply circuit, which may occur singly or in combination.

Changes in the frequency of the supply circuit.

Change in the number of poles of the motor, which may be independent of all other changes because a faster or slower speed may be desired, or it may follow as a result of a change in frequency in order to keep the same speed on the driven machine when the motor is operated on the new frequency.

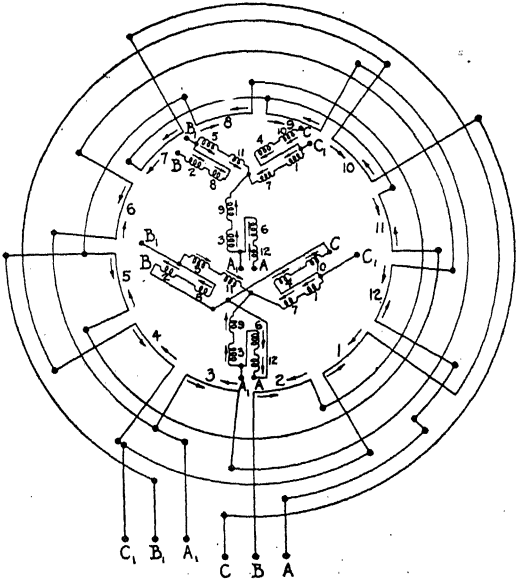

Fig. 228. Conventional Three-Phase, Two-Speed, Four- and Eight-Pole Diagram. Parallel-Star Connection for Four Poles. Series-Star Connection for Eight Poles. For Four Poles A_1, B_1, and C_1 Are Leads and A, B, and C Are Connected Together. For Eight Poles A, B, and C Are Leads and A_1, B_1, and C_1 Are Open

Changes in Voltage Only, All Other Conditions Remaining the Same. This is the simplest change that can be made in an induction-motor winding. Most of these changes are covered in Table IX. You must constantly bear in mind that a motor may

always be reconnected for a lower voltage so far as the insulation is concerned, but it should not be reconnected for a voltage much in excess of that for which it was designed and insulated.

Changes in Phase Only. The most frequent problem in this connection is the change from two- to three-phase, and vice versa. Theoretically, for the same voltage there should be about 25 per cent more total turns in a two-phase winding than in a three-

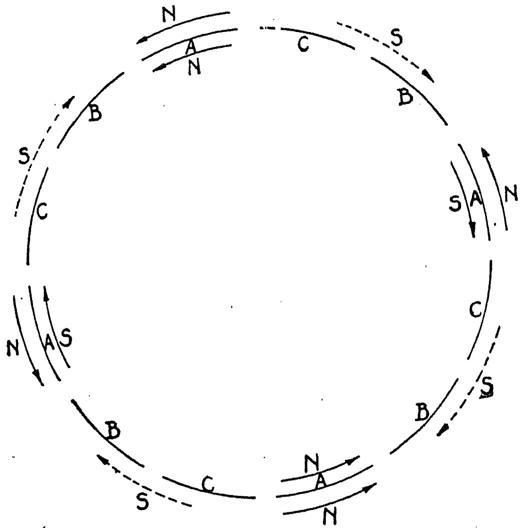

Fig. 229. Diagram Illustrating Location of Poles for Two-Speed Connection Shown in Fig. 228. Arrows Inside Winding Circle Show Poles Formed by the A Phase Windings on Four-Pole Connection. Arrows Outside Winding Circle Show Four Poles of Same Polarity Formed by Windings, and Four Resulting Consequent Poles of Opposite Polarity Are Shown by Dotted Arrows; This Makes Eight Poles Total and Gives Half the Speed of Four-Pole Connection

phase winding. If a three-phase motor be reconnected for two-phase at the same voltage and the same number of coils, it will exhibit all the symptoms of a motor operating at approximately 25 per cent over-voltage, and would overheat to a dangerous degree after a short period of operation. On the other hand, a two-phase motor reconnected as a three-phase motor at the same voltage and the same number of coils will exhibit all the signs of a motor

operating at 20 per cent under-voltage. In this case there are too many turns in series, and one-fifth of the total coils might be deadened so as to secure the proper voltage on the remaining 80 per cent. These dead coils should be distributed as symmetrically as possible around the machine so as to balance the voltage. It is not advisable to connect coils in parallel, as this gives a chance for

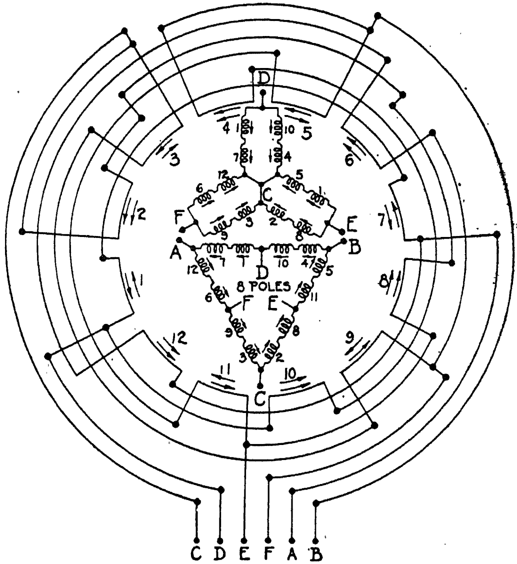

Fig. 230. Conventional Three-Phase, Two-Speed, Four- and Eight-Pole Diagram. Parallel-Star Connection for Four Poles. Series-Delta Connection for Eight Poles. For Four Poles D, E, and F Are Leads and A, B, and C Are Connected Together. For Eight Poles, A, B, and C Are Leads and D, E, and F Are Open

unbalanced winding and circulating local currents, which may cause excessive heating.

The current taken by a three-phase motor at full-load and at any given voltage is about 12.5 per cent greater than the current taken by a two-phase motor under the same conditions. Hence, in order to keep the current density the same the three-phase

horsepower will have to be cut down about 12.5 per cent from what it was in the two-phase connection.

The so-called Scott or T connection may be used in operating a two-phase motor on a three-phase circuit. When this connection is used 14 per cent of the coils in one phase of the two-phase

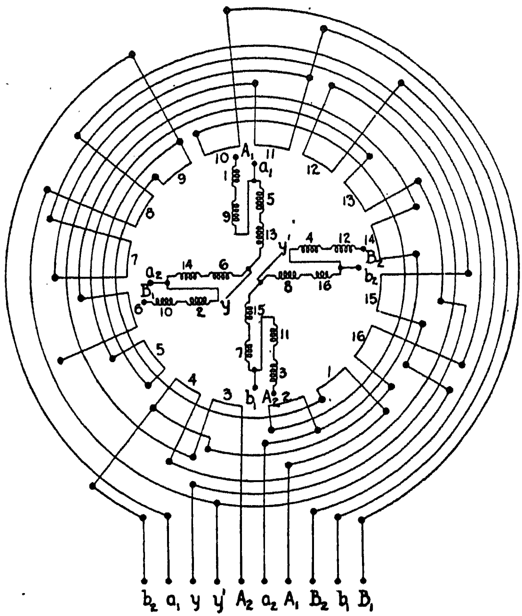

Fig. 231. Conventional Two-Phase, Two-Speed, Four- and Eight-Pole Diagram. (For Eight Poles Connect y and y'. Use A_1, A_2, and B_1, B_2 for Leads and Leave a_1, a_2 and b_1, b_2 Open. For Four Poles Connect A_1, B_1 Together and A_2, B_2 Together; Leave y and y' Open and Use a_1, a_2 and b_1, b_2 for Leads

machine are omitted as symmetrically as possible around the machine. The connections are shown diagrammatically in Fig. 226.

This connection would give fairly good results if the coils between A_1 and B_1 were so situated on the machine that they would be acted upon by the magnetic field in exactly the same manner as the coils between B_1 and A_2. Practically, as motors are wound nowadays, this is rarely possible, and if the usual winding

is connected in T there are practically always unbalanced currents in the three phases. The current in the high phase will be about 20 per cent greater than the current in the low phase. This results in a poorer performance in torque, power-factor, efficiency, and heating, as illustrated by the actual test data in Table X, which shows in three parallel columns the performance of a standard

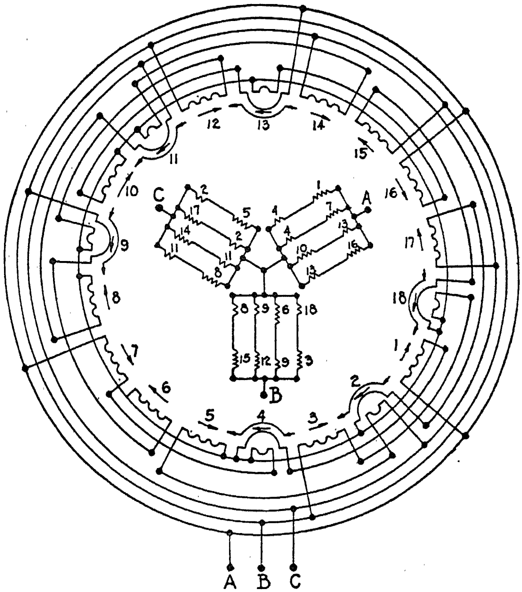

Fig. 232. Conventional Three-Phase, Six-Pole, Four-Parallel Star Diagram

motor wound with normal two-phase coils, with two-phase coils connected in T and run on three-phase, and with normal three-phase coils. The efficiency on the T connection is 1.6 per cent lower, the power-factor 5.2 per cent lower, the starting torque 38 per cent lower, the maximum torque 4 per cent lower and the temperatures from 8 to 13.5 degrees higher than on the normal three-phase winding. This showing certainly puts this connection

in the C class. The motor operates (if it can start the load), but it should not be considered where a large number of motors are concerned or where the cost of power is given any weight. This summary shows that changing from two-phase to three-phase, and vice versa, is at best very unsatisfactory, and the advice given in practically all cases of this nature is "Don't!" Better rewind with normal three-phase coils and avoid the host of troubles which follow in the train of an indifferently operating motor.

Of course, one essential in any phase reconnection is to go over the winding and rearrange the "phase coils," or coils having heavier insulation, so that they will come properly at the ends of the groups where the voltage is highest. This is illustrated in Fig. 222.

One case of voltage and phase change which works out very well is the change from three-phase, 550 volts to two-phase, 440 volts, or vice versa. This uses all the turns in the winding for either connection, since the two-phase voltage should be about 80 per cent of the three-phase and since the higher voltage on the three-phase cuts down the current, which would otherwise be higher than the two-phase circuit. If the phase coils are rearranged there is practically no objection to such a reconnection, and the motor will give essentially the same performance on either connection.

Table IX shows the possibilities of these interphase connections, as well as the different voltage changes. For example, take the case just cited. Follow the horizontal line marked "2-Ph. Series" to the first vertical column headed "3-Ph. Series Star." The figure is 125. This means that a motor originally connected two-phase series, if reconnected three-phase series, should be operated on 125 per cent of the original voltage. Or, if the two-phase voltage was 440, the three-phase would be $1.25 \times 440 = 550$ volts. The convenience of Table IX is demonstrated for phase changes, as well as voltage changes, or for combinations of both.

Changes in Frequency. The occasion often arises for changing 25-cycle motors to 60-cycle, and 60 to 25. There is also some changing done from 60 cycles to 50, and from 50 to 60. Occasionally 40-cycle motors are changed to 60, but these changes are too infrequent to be of very general interest.

In all cases of changed frequency the question that first arises is: How is the resulting change in speed to be taken care of? The synchronous speed of any motor (which is only a slight per cent higher than the full-load speed) is given by the general expression $\frac{\text{alternations per minute}}{\text{number of poles}}$. This would be $\frac{3000}{\text{number of poles}}$ for 25 cycles, $\frac{7200}{\text{number of poles}}$ for 60 cycles, etc. If, then, the frequency is changed and the number of poles left the same, the resulting r.p.m. will vary directly as the frequency. This immediately brings up two questions: First, is the mechanical design of the rotating part adequate to allow such a change in speed? Second, can the speed of the driven machine be adjusted to suit the new speed on the motor?

Consider first the case where the frequency is changed and the number of poles remains the same. The resulting change in speed in this case is taken care of either by applying the motor to a new load or by changing the pulleys on the old load so as to keep the same r.p.m. on the driven machine. The next thing that must be considered is the necessary change in the voltage applied to correspond to the change in frequency, or the other way about, if the new circuit at the new frequency has the same voltage as was used with the original frequency, how can the coils in the motor be reconnected so as to get the proper voltage on each coil?

The easiest rule to remember is: apply voltage on the motor in exactly the same way as the frequency is varied. If this be done the magnetic field in the iron will remain the same and the current in the stator and rotor coils will remain the same, if the motor is working against the same torque. This is another way of saying that if the frequency and voltage are varied together, the motor will develop the same torque at all times and have flowing in it approximately the same current. As noted before, if the torque remains the same, the horsepower developed will vary directly as the applied frequency. For example, a 60-cycle, 50-horsepower motor operated on 25 cycles at 41.6 per cent of its original voltage would develop the same normal full-load torque, which would mean 20.8 horsepower.

The case most commonly met with, which is changing from 25 cycles to 60 cycles, can often be taken care of by impressing twice the voltage on the coils on 60 cycles as on 25 cycles, or in a concrete case operating a 220-volt, 25-cycle motor on 440 volts, 60 cycles, at about double the horsepower Theoretically, this should be $60 \div 25 = 2.4$ times the voltage, instead of twice, and the resulting horsepower would be 2.4 times. However, 2.4 times is usually hard to get, and two times comparatively easy In this case suppose the motor is connected in series star for 440 volts on 25 cycles and it is desired to run it on 440 volts, 60 cycles. It should then be connected in parallel star and run on 440 volts, which would have the same effect as impressing 880 volts on the original series connection. On 60 cycles the motor would then run 2.4 times as fast and develop about twice the horsepower.

Sixty-cycle motors are often run on 50 cycles without change. From the rule above—that the voltage must vary with the frequency to keep the same magnetic densities—it will be noted that the densities on 50 cycles at the same voltage will be six-fifths of the 60-cycle densities. The motor will then operate as if it had 120 per cent of normal voltage impressed. This will result in increased iron losses, which make the motor hotter; the decreased speed on 50 cycles with same number of poles makes the ventilation poorer; so the output of the motor in horsepower should be reduced to keep down the copper losses. This is logical in another way, because the horsepower at five-sixths speed should not be expected to be more than five-sixths of its full speed value. Another point that should be watched in changing frequency if the motor has a squirrel-cage rotor is that the rotor winding has enough resistance to give the proper starting torque. As the frequency is raised the resistance of the short-circuiting rings at the ends of the rotor winding should be increased to keep the same relative value of starting torque to full-load torque. As long as the motor starts its load satisfactorily no change is necessary, but if trouble is experienced the short-circuiting rings may have to be changed for rings of higher resistance. Conversely, when decreasing the frequency the resistance can be reduced to advantage, thereby cutting down the rotor copper loss and the heating.

Where the frequency is to be changed but it is desired to keep the same speed, the number of poles must be changed in the same ratio as the frequency, or as nearly so as possible. For example, if a motor has four poles and is operated on 25 cycles it will have a synchronous speed of $3000 \div 4 = 750$ r.p.m. If the motor is to have the same speed on 60 cycles, the nearest possible pole number is 10 and the synchronous speed will be $7200 \div 10 = 720$. It is apparent that in very few cases of this kind is it possible to reconnect the same winding. The main reason for this is in the throw or pitch of the coil. In the four-pole winding the individual coil spans approximately one-fourth of the stator bore, and in the ten-pole winding normal coils should span about one-tenth of the stator bore.

In discussing the fundamental e.m.f. equation it was shown that the throw of the coil has an effect on the generated e.m.f. This makes hardly possible such a condition as connecting a winding for ten poles when the individual coils have a four-pole throw. When reducing the frequency the number of poles should become smaller to keep the same speed, and this introduces another difficulty in the magnetic circuit. In reconnecting the winding the object is to keep the total magnetic flux in the machine the same as it was originally. This keeps the magnetic density in the teeth constant. This total magnetic flux is divided up into as many equal parts or circuits as there are poles. The iron in the stator core between the bottoms of the slots and the outside of the core has to carry the flux for each magnetic circuit. Consequently, if there are ten poles and ten magnetic circuits the core iron below the slots has to carry at a given cross-section one-tenth of the total magnetic flux. With the same total magnetic flux, if there are only four poles and four magnetic circuits, the same cross-section of core has to carry one-fourth of the total magnetic flux, and this it is probably unable to do. This is the reason why the rotor diameter and stator bore of a 25-cycle machine are smaller than those of a 60-cycle machine of the same horsepower and speed, although the outside diameter may be nearly the same. It is to get a larger cross-section behind the slots for the passage of the magnetic flux, since the total flux is divided into fewer parts, owing to the smaller number of poles.

From this it follows that a machine may in general be rewound or reconnected for a larger number of poles, but that great caution is required in reconnecting for a smaller number of poles. This leads up to the statement that it is easier to rewind or reconnect 25-cycle machines for 60 cycles than it is to reconnect 60-cycle machines for 25 cycles. This follows logically from the physical fact that there is more copper and more iron in 25-cycle machines for the same horsepower, voltage, and r.p.m. than in 60-cycle machines. It is always easier to make changes where there is a larger supply of material available. Another condition that is against changing the number of poles on a squirrel-cage motor is the current in the short-circuiting rings of the rotor winding. These rings are in nearly the same case as regards current that the primary core is as regards magnetic flux. That is to say, the total secondary amperes, which remain nearly the same if the reconnection is done properly, are divided into as many circuits as there are poles, and it follows at once that the smaller the number of poles the larger must be the cross-section of the short-circuiting rings, although the total secondary amperes remain nearly the same. Altogether, the possibility of reconnecting for different numbers of poles when changing frequency is usually a matter for the designing engineer to investigate.

Changes in the Number of Poles, All Other Conditions Remaining the Same. The need for such changes comes from the desire to speed up or slow down the driven machine to meet new requirements. It might be broadly stated that there are many cases where a change of two poles is permissible, as, for example, changing from four poles to six, or from ten to eight, and the like. The change would consist in rearranging the phase coils to agree with the new grouping and checking the distribution factor, as mentioned above, to note its effect on the voltage. The proper diagram for the new speed can then be made up by comparison with the corresponding typical diagram. It is often possible to get a fair operating half speed by connecting for twice the number of poles, as shown in Figs. 228, 230, and 231. Practically all reconnections involving pole changes are Class B changes, in that they give only a fair operating performance.

The procedure in checking up a machine to see if it can be

reconnected is first to ascertain the existing connection and the throw of the coils in order to know what the possibilities are in the way of number of turns and throw. Second, if it is a phase or voltage change, find directly from Table IX what connections will give approximately the proper new voltage and new phase. If any one of these connections is possible with the number of poles in the machine, select it as the new connection and arrange the phase coils properly at the beginning or ending of the groups, or at each end of the groups if there are enough of them in the old winding. Since the speed has not changed the horsepower should remain approximately the same, and the current in the coils themselves will remain somewhere near the original. If the frequency is to be changed either independently or in conjunction with a phase or a voltage change, the applied voltage should be changed in the same direction and by the same amount as the frequency is changed; if the voltage is to remain unchanged the number of turns in series in the coils should be changed in the opposite direction to the frequency and by the same amount. For example, if a 25-cycle motor is to be run on 30 cycles, it should have the voltage increased 20 per cent, or else it should have the groups reconnected so that there will be 20 per cent less turns in series, and be run on the same voltage.

If the number of poles is to be changed, and consequently the speed, check first the effect of the coil throw with the new number of poles. Then think of the motor winding as generating e.m.f. and bear in mind that with a constant field a higher speed will generate more e.m.f. and a slower speed less e.m.f. Converted into voltage this means that with a higher speed a higher voltage should be applied in direct proportion, and that with a lower speed a lower voltage should be applied. If the voltage cannot be changed try to change the diagram of group connections so as to vary the number of turns in series in the right way; i.e., if voltage should be increased the same effect can be obtained by decreasing the number of turns a like amount. In all these cases it is the voltage per turn or per inductor which counts, just as in a transformer, and a careful consideration of the effect of different connections will show whether the desired change in voltage per inductor is being accomplished.

As a concrete example of the foregoing, assume a 25-horsepower, four-pole motor operating on 40 cycles, two phases, 220 volts. It is desired to know whether it can be reconnected to operate on 60 cycles, three phases, 550 volts at the same speed and horsepower.

An inspection of the machine shows that it has 72 slots and 72 coils and that any individual coil lies in slots 1 and 15, also that the groups are connected in parallel. Since there are $72 \div 4 = 18$ slots per pole, each slot is $180 \div 18 = 10$ electrical degrees and 14 slots $= 140$ electrical degrees. (The throw of 1 to 15 means spanning 14 slots.) The sine of one-half of 140 degrees (or 70 degrees $= 0.94$) $=$ chord factor; or, figured by the formula without trigonometry, since there are 18 slots per pole and a throw of 1 to 15 means dropping 4 slots from exact pitch, the chord factor $= \sqrt{\frac{18^2 - 2 \times 4^2}{18^2}} = 0.948$. The synchronous speed of the motor on 40 cycles as it stands is $4800 \div 4 = 1200$ r.p.m. To get this same speed on 60 cycles it is evident the motor will have to be connected for $7200 \div 1200 = 6$ poles. If the throw of the coils be left 1–15 they will throw two slots further than full pitch, since $72 \div 6 = 12$ slots per pole, and 1 to 13 would be exact pitch. Throwing the coil over pitch has the same effect as throwing it under pitch so the new chord factor on six poles $= \sqrt{\frac{12^2 - 2 \times 2^2}{12^2}} = 0.97$, or sine of one-half of 150 degrees $= 0.98$. Taking into account the changes in phase, poles, frequency and chording, the new applied voltage per phase should be $\frac{880}{3} \times \frac{4}{6} \times \frac{60}{40} \times \frac{0.98}{0.94} = 305$ volts.

The explanation of this expression by terms is: The first term, $880 \div 3$, comes from the change in phase from 2 to 3. Since the original connection was in parallel and was for two-phase, the voltage across one phase in series would be $2 \times 220 = 440$, and the voltage across both phases in series would be $2 \times 440 = 880$ volts. If the winding is divided into three separate phases not interconnected, the applied voltage on each phase would be $880 \div 3$. The next term, $4 \div 6$, represents the change in poles. A motor with six poles would run slower on the same frequency than a motor with four poles and would generate less counter-e.m.f.

Consequently, the applied voltage should be decreased in the same proportion. This should not be confused with the fact that the frequency is being changed in this case and the speed kept the same, for a separate factor is introduced to take care of the frequency. The pole change should be considered as an item separate from the frequency change. The next term, 60÷40, is due to the change in frequency and is the application of the rule to change the applied voltage directly as the frequency is changed. The last term, 0.98÷0.94, is due to the difference in chord factor. With a throw of 1–15 the coils are more effective to generate counter-e.m.f. on the six-pole than on the four-pole connection by the ratio of the chord factors 0.98 to 0.94; hence the applied voltage should be raised with the counter-e.m.f.

As just stated, this figure of 305 volts means that if the winding is divided into three separate phases not interconnected in any way the voltage should be 305 volts across each phase. If the three phases are connected in star, as in Fig. 216, the applied voltage should be $1.73 \times 305 = 528$ volts. Since this is only about 3.5 per cent off from the 550 volts which is to be used, this motor will operate satisfactorily. This calculation for voltage so far neglects the difference in the so-called "distribution factor" between three phase and two phase, but this is immaterial. This factor acts the same way as the chord factor, and is about 0.956 for any normal three-phase windings and 0.903 for any normal two-phase winding, so that the applied voltage should really be $528 \times \frac{0.956}{0.903} = 558$ volts, which is almost exactly what is required. This motor could then have its phase coils rearranged for six poles and be connected series star and would be proper for the new conditions. The changes involved do not materially affect the slip, so that no change is required in the rotor winding. This example is not intended as an exact method of design, but simply illustrates a rough calculation to show what are the possibilities.

After a motor is reconnected or after any change is made in the winding, start it up slowly, throwing the load on gradually and observing carefully to see if there are any signs of distress, such as sudden heating, noise, or mechanical vibration. If the motor seems to operate normally, read the amperes in each phase

and the voltage across each phase to see that they are balanced and are of reasonable amount. The full-load current for three-phase, 550 volts is somewhere near one ampere per horsepower for normal motors of moderate speeds between 5 and 200 horsepower. At other voltages the current will be inversely as the voltage, that is, at 440 volts, three phases, about 1.25 amperes per horsepower. On two phases the current per phase is about 87 per cent of the corresponding three-phase value. If the readings as above look reasonable, place a thermometer on the stator iron and another on the stator coils and note at 15-minute intervals for an hour, and at half-hour intervals thereafter, till the temperature is constant. The speed should be checked at intervals. If the r.p.m. show a tendency to decrease rapidly or fall below 90 per cent of synchronous speed it may be suspected that the rotor has too much resistance and is getting hot. By making all these checks, reasonable assurance may be had that the reconnection is satisfactory and that damage to the machine is avoided.

Conclusion. From the foregoing it can be seen that all changes, whether of phase, voltage, poles or frequency, may be considered as voltage changes and reduced to such terms. In making such calculations and comparing the results it is best not to apply a voltage that differs from the figured proper voltage by more than plus or minus ten per cent. The general effect of high and low voltage may be expressed briefly, thus:

High Voltage

(a) Increases magnetic density
(b) Increases magnetizing current
(c) Decreases "leakage current" (leakage reactive component)
(d) Increases starting torque and maximum torque
(e) Decreases slip or change in speed from no load to full load
(f) Decreases secondary copper loss
(g) Increases iron loss
(h) Usually decreases power factor
(i) May increase or decrease efficiency and heating, depending upon the proportions of primary copper loss and iron loss in the normal machine and also the degree of saturation in the iron

Low Voltage

(a) Decreases magnetic density
(b) Decreases magnetizing current
(c) Increases leakage current

(d) Decreases starting and maximum torque
(e) Increases slip
(f) Increases secondary copper loss
(g) Decreases iron loss
(h) Usually increases power factor
(i) May increase or decrease efficiency and heating, depending upon the proportions of primary copper loss and iron loss in the normal machine and also the degree of saturation in the iron

Finally, it may be stated that:

(1) Changes in voltage alone are the easiest class of changes and can usually be made.

(2) Changes in number of phases alone can rarely be made satisfactorily and are usually only makeshifts.

(3) Changes in number of poles are limited, due to the mechanical form of the coils.

(4) Changes of frequency alone or in combination with voltage or phase can sometimes be made if changes in speed are not objectionable.

(5) Complicated changes should not be attempted except by persons of some experience and should be handled with caution.

(6) If the peripheral speed of the rotor (which equals rotor diameter in feet×3.14×r.p.m.) exceeds 7000 feet per minute on any proposed change, the maker of the motor should be consulted before making the change.

(7) In case of any doubt on any point refer to the manufacturer of the machine.